

NASA Technical Memorandum 104366

1N-02

14440

P29

Icing Simulation: A Survey of Computer Models and Experimental Facilities

M.G. Potapczuk and J.J. Reinmann
*Lewis Research Center
Cleveland, Ohio*

(NASA-TM-104366) ICING SIMULATION: A SURVEY
OF COMPUTER MODELS AND EXPERIMENTAL
FACILITIES (NASA) 29 p CSCL 01A

N91-23087

63/02 Unclass
0014440

Prepared for the
68th AGARD Fluid Dynamics Panel Specialists Meeting
Toulouse, France, April 29—May 1, 1991

NASA

Icing Simulation: A Survey of Computer Models and Experimental Facilities

M.G. Potapczuk

J.J. Reinmann

NASA Lewis Research Center,
Cleveland, Ohio 44135

Summary

This paper is a survey of the current methods for simulation of the response of an aircraft or aircraft subsystem to an icing encounter. The topics discussed include: 1) computer code modeling of aircraft icing and performance degradation, 2) evaluation of experimental facility simulation capabilities, and 3) ice protection system evaluation tests in simulated icing conditions. Current research, which is focussed on upgrading simulation fidelity of both experimental and computational methods, is discussed. The need for increased understanding of the physical processes governing ice accretion, ice shedding, and iced airfoil aerodynamics is examined.

1. Introduction

The safe operation of an aircraft under icing conditions is a topic of current interest in the aerospace community. A need for development of icing simulation methods has been identified by aircraft manufacturers and certification authorities alike.¹ Reinmann, et al.² identified several reasons for the current interest in icing; '(1) the more efficient high by-pass ratio engines of today and the advanced turboprop engines of tomorrow have limited bleed air for ice protection, so the airframers are seeking more efficient systems; (2) airfoil designers do not want their modern, high-performance surfaces contaminated with ice, so they are intensifying pressure to develop ice protection systems that minimize residual ice and thereby allow the airframer to keep airfoil surface area to the minimum; (3) new military aircraft requiring severe weather capability are currently under development; (4) some existing military aircraft, being used primarily for training missions, are experiencing foreign object damage (FOD) due to icing conditions they would not normally encounter in combat; (5) designers of high performance military aircraft want to avoid burdening the aircraft with ice protection, so they want to know where and how much ice will build on the aircraft and whether the aeroperformance penalties are acceptable; (6) designers of future high performance aircraft with relaxed static stability need to know how their aircraft will perform with contaminated aerodynamic surfaces; (7) little is known about the effects of ice accretion on the

operation and performance of advanced turboprops, and whether or not ice protection will be required; and (8) the FAA has certified only one civilian helicopter for flight into forecasted icing, which implies a strong need for support of helicopter icing.'

Satisfying these needs can require lengthy and expensive flight test programs if unassisted by icing simulation methods. Additionally, finding icing conditions over the full certification icing envelope can not be done within a reasonable time frame. Thus, various methods for simulation of icing conditions are an important and necessary part of the design and certification of aircraft and ice protection systems.

Initial efforts at icing simulation took place in the late 1920's and early 30's. These activities are described in References 3-8. World War II precipitated an urgent need for research into icing simulation and ice protection system design. In the United States, this led the National Advisory Committee for Aeronautics, NACA, to build the Icing Research Tunnel (IRT) at the Lewis Research Center in Cleveland, Ohio during the early 1940's. Initial activities in the IRT covered a broad range of icing problems. Many of these included the development of ice formations on aerodynamic surfaces and the evaluation of aerodynamic performance degradation. A complete bibliography of the NACA research activities during this period is available as a NASA TM.⁹

Icing simulation activities have increased dramatically during the period from the late 1970's to today. Wind tunnel and flight research has been conducted by many organizations in North America and Europe. In addition, the advent of high speed computer systems has allowed the development of sophisticated computer simulations of ice accretion processes and resulting performance degradation. As a result, a new role has been created for wind tunnel and flight research, that is development of code validation databases.

Despite the long history of icing research, there still remains a significant number of unresolved issues in the process of icing simulation. These issues range from the fundamental physics of the icing process to the mechanisms underlying the ice removal process. The ability of the aerospace community to predict the effects of aircraft icing and the performance of potential ice protection systems will be strengthened by addressing these issues and

incorporating an increased understanding of the icing process into simulation efforts. This paper seeks to identify the issues of current icing simulation research and to suggest how current simulation methods might be improved.

2. The Physics of Icing and Ice Protection

2.1 Ice accretion physics

Icing occurs when an aircraft encounters a cloud containing super-cooled water droplets, which impact aerodynamic surfaces and freeze, forming non-aerodynamic shapes on these surfaces. Incoming water droplets can vary in size from 2 or 3 microns to over 40 microns. Typically, smaller droplets tend to follow the airflow over the surface while larger droplets follow more straight-line paths to the surface. Upon impact on the aircraft surface, the water droplets can either freeze immediately or exist as a water/ice mixture. These two conditions are dependent on environmental parameters such as, temperature and cloud liquid water content (LWC), and on aircraft surface conditions such as, skin temperature and surface roughness.

The basics of the ice accretion process, as described above, have been known for some time. However, there are details of the process which are still not completely understood. Recent research in these areas has focused on development of alternatives to the physical model currently used in ice accretion codes. The current model was proposed by Messinger¹⁰ nearly forty years ago and includes the following concepts: in rime icing conditions (*i.e.* air temperatures well below freezing and low LWC values), all cloud droplets freeze upon impact with the surface. In glaze icing conditions (*i.e.* air temperatures close to freezing and high LWC values), only a fraction of the water will freeze upon impact, and the remainder will run back. The close-up photography of Olsen and Walker,¹¹ as shown in Figure 1, indicates that some fraction of the water which remains in the liquid state after impact may not run back along the surface, as is currently assumed. This water may remain in pools formed by the surrounding ice, thus requiring an alteration of the current model of the ice growth process. Splashing of incoming water droplets^{12,13} may occur under certain conditions, which could result in less water on the surface than indicated by droplet trajectory calculations. It is also suspected that the initial conditions of the icing process may have a significant impact on the subsequent ice growth. Factors such as the initial surface roughness, the surface tension at the air-water-airfoil interface, the water droplet size, and the boundary layer transition location can all influence the final ice shape.^{12,13}

Following up on Olsen's work, Hansman, et al.¹⁴ further studied the icing process. Figure 2 shows the test

setup used to observe ice growth on a cylinder. By illuminating the ice surface with a laser sheet, they constructed a time history of the ice profile (shown in the middle diagram). This sequence of profiles suggested a three zone heat transfer model that differed significantly from the Messinger model. Hansman's model attempts to account for the changing conditions on the airfoil surface by tying the transition from the smooth to rough region to the boundary layer transition.

It is hoped that by understanding the ice accretion process more completely, some of the empiricism present in current icing models may be eliminated. This should result in more robust models providing simulation of the icing process over a broader range of the icing envelope.

2.2 Iced airfoil aerodynamics

Ice accretions on the wing leading edge lead to increases in drag, decreases in lift, changes in the moment distribution, a decrease in the value of $C_{L_{max}}$, and a decrease in the stall angle. These effects are due to a change in the pressure distribution on the wing and to increased viscous losses.

From the point of view of effects on aerodynamics, ice growths have two relevant length scales. Ice growth structures on the scale of the boundary layer height can be considered as roughness elements. Structures larger than the boundary layer height and on the order of the airfoil thickness influence the aerodynamics in different ways and are typically referred to as ice shapes or ice caps.

Ice shapes can result in changes in the pressure distribution over the airfoil, development of separated flow regions, early transition of the boundary layer, and premature stall. Ice roughness can result in thickening and early transition of the boundary layer, alterations to the pressure distribution, and increased drag. Both types of ice growth can lead to a decrease in maximum lift.

The results of Ingelman-Sundberg, et al.¹⁵ suggest that ice roughness can result in a decrease in $C_{L_{max}}$ and that a glaze ice shape can result in an even larger decrease for single-element airfoils. Their results also indicate that roughness and ice caps produce approximately the same level of change in $C_{L_{max}}$ for high lift configurations. Potapczuk and Berkowitz¹⁶ have measured the changes in lift, drag, and pitching moment for a two-dimensional model of a Boeing 737-200 ADV wing section, in both cruise and high-lift configurations, as ice accumulated on the surface. Their results indicated continual increases in the effects of ice accumulation on drag. The changes to lift and pitching moment were not evident until the angle of attack was varied from the condition at which the ice was accumulated.

It is difficult to establish any clear trends applicable to all icing encounters, however, it is safe to say that the degree of aerodynamic degradation due to icing is dependent on airfoil geometry and attitude, ice accretion time, and icing cloud conditions. As a consequence of this dependence, it is apparent that simulation of iced airfoil aerodynamics is necessary to thoroughly evaluate the behavior of a given aircraft encountering icing conditions.

The changes in airfoil aerodynamics due to icing apply equally to helicopter rotors. Bond et al.¹⁷ has shown that rotor icing can lead to increases in rotor torque on the order of 25 to 50 percent. Additional results indicate that ice shedding events can reduce rotor torque by 5 to 10 percent temporarily, thus producing loading transients which can increase system vibration. Asymmetric ice shedding can pose a considerable problem due to out-of-balance conditions which may lead to high vibratory loads on the rotor system.¹⁸

2.3 Ice Protection Systems

There are two approaches to aircraft protection from icing; anti-icing and de-icing. Anti-icing is the prevention of ice growth on critical aircraft lifting surfaces, while de-icing is the removal of accumulated ice before significant degradation of aircraft performance. Anti-icing methods provide the greatest safety factor but require the greatest amount of energy. De-icing methods on the other hand may provide appropriate safety with lower energy requirements.

Either approach to ice protection may be implemented in a number of ways. There are essentially three categories of ice protection techniques: chemical, mechanical, and thermal. Chemical methods typically consist of exuding some type of material on the wing surface that mixes with the ice and depresses the freezing point. Mechanical methods utilize various devices that break the ice-wing surface bond by imparting a strain or an impulse to the outer structure of the wing. Thermal methods melt or evaporate the ice by heating the wing surface through a variety of methods.

The conventional approach for protection of commercial transport vehicles for the past thirty years has been anti-icing through the use of hot compressor bleed air. Hot air flowing inside the wing raises the temperature of the leading edge above a level which will allow ice to form on the surface. Usually the temperature of the leading edge is high enough to evaporate any water on the surface. This prevents runback water from refreezing on the wing surface aft of the heated area.

But more recently, as jet engine manufacturers have begun increasing engine by-pass-ratios to achieve higher efficiencies, the engine cores have become smaller and the amount of hot bleed air available for anti-icing has

shrunk significantly. First priority for bleed air is given to cabin pressurization and air conditioning. To cope with this loss of bleed air, airframers are either eliminating ice protection from selected components, or considering alternatives to compressor bleed air. Attractive alternatives are more energy-efficient deicing systems that allow some ice buildup before actuating the deicer. Helicopters, general aviation aircraft, and light transports, all with relatively small payload fractions and low power margins, have always relied on these more efficient ice protection systems.

As alternate ice protection methods are incorporated into aircraft designs, there will be a need to simulate their capabilities either computationally or in ground testing facilities such as icing wind tunnels. It therefore will be necessary to fully understand these experimental simulation activities.

3. Analytical Simulation Methods

Analytical icing simulation has been based on a combination of correlations, computer codes, and theoretical models of the icing process and its consequences. This section will discuss some of the current methods used for modeling ice accretion, aeroperformance degradation, and ice protection system performance. For further information on recent progress in analytical modeling see the report by Shaw, et al.¹⁹

3.1 Ice Accretion Computer Models

Ice accretion codes have been developed by several researchers.²⁰⁻²³ Typically, these codes calculate the flowfield surrounding the airfoil, determine the droplet impingement pattern, and calculate the amount and shape of ice that grows on the surface. Results of these codes are compared to ice shape tracings from tests in icing wind tunnels. Comparisons to flight data have also been performed,²⁴ but are not as common due to the difficulty in obtaining actual in-flight ice shapes.

Current ice accretion models are based on the control volume approach, such as that of Messinger.¹⁰ In this model, a mass balance and energy balance are performed in order to determine the amounts of water that either freeze or runback along the surface to the next control volume. This control volume approach is depicted in Figure 3. The key factors influencing the ice growth in this model are the mass of incoming water from the cloud and from the upstream control volume, the convective heat flux, and the heat flux into the surface at the ice-body interface.

The ability to accurately calculate the incoming water from the cloud has been demonstrated quite convincingly by several comparisons between calculation and experiment. The accuracy of these methods is deter-

mined by evaluating the local collection efficiency calculation along the surface of the airfoil. The local collection efficiency, in a 2D sense, is defined as the ratio of the vertical distance between two particles at the upstream release point to the distance along the airfoil surface between their impact points. An example of the collection efficiency calculation is shown in Figure 4, where the calculated value along the surface of a NACA 65-015 airfoil is shown to agree quite closely with experimental results.

The convective heat flux is influenced by the development of the boundary layer on the rough iced airfoil surface. As such, the pressure distribution, roughness level, and transition location all play an important roll in the ice growth process. Currently these effects are accounted for by correlations between the heat transfer coefficient and the cloud icing conditions. A typical example is found in the roughness correlation in LEWICE,²¹ the ice accretion code developed by NASA.

Hansman, et al.¹⁴ has indicated an alternate approach which tries to incorporate more of the physics of the process, as it is currently understood. His results have shown a marked improvement for cases of ice accretion on cylinders. Figure 5 shows a comparison of calculations using LEWICE with the original ice accretion model and with Hansman's²⁵ updated model. The updated analysis and experiment agree remarkably well. This multizone model is undergoing further study and refinement, especially regarding surface roughness and its effect on heat transfer and transition location.

Most computer codes treat the heat flux into the surface as a specified constant value during the entire simulation. This constant is normally taken to be zero thus prescribing an insulated boundary. However, heat flux into the airfoil surface may play an important role in the development of the ice shape, especially in the initial moments of the ice accretion. This possibility along with the desire to model thermal de-icing systems has led to the development of computational methods for evaluating the heat transfer between the ice and the underlying airfoil structure. These models will be discussed more fully in the section on ice protection system simulation.

Until recently, these computer models have been strictly two dimensional, calculating ice shapes for chord-wise slices along a wing surface. Three dimensional ice accretion codes are currently under development as extensions of the well established 2D methods. Potapczuk and Bidwell²⁶ have calculated the ice growth on a MS-317 wing section with 30° sweep angle. Guffond has calculated ice growth on the tip of a helicopter rotor.²⁷ These efforts, while promising, require further development before use as an engineering tool.

A recent research activity has been the coupling of the ice accretion code with methods for evaluation of the

performance degradation due to icing. Cebeci²⁸ has coupled a two-dimensional interactive boundary layer (IBL) method with the LEWICE ice accretion code in order to simulate the entire icing process. Figure 6, taken from Shin et al.,²⁹ shows the results for several icing conditions. The most encouraging aspect of this calculation is the ability of the code to determine the drag rise at temperatures just below freezing. The results for the ice shape comparison agree quite well. The differences between the code and experiment for the actual drag values suggest that the method requires further refinement.

3.2 Performance Degradation Computer Models

Determination of an aircraft's response to an icing encounter requires the evaluation of performance changes resulting from a wide variety of ice accretion shapes. This necessitates the use of an extensive series of tests either in flight or in a wind tunnel. In either case, the use of appropriate computational methods could decrease the amount of required testing and thus decrease the cost and time requirements of the certification process. As such, computer codes currently being used for evaluation of clean or un-iced aircraft are being adapted for use in evaluation of icing performance degradation.

Until recently, performance changes for iced airfoils have been computed using empirical correlations such as those of Gray,³⁰ Bragg,³¹ and Flemming et al.³² These methods work well over a restricted set of environmental conditions, but are not adequate for general use by potential aircraft designers. As a result, computer codes have also been developed to evaluate the changes in performance of airfoils, wings, and rotors due to the presence of ice on critical surfaces.

Cebeci²⁸ has used the IBL code to evaluate the performance degradation of a NACA 0012 airfoil with a simulated leading edge ice shape. Comparisons of the IBL results with Bragg's wind tunnel data³³ are shown in Figure 7. These results indicate that the IBL method can determine the aerodynamic losses associated with ice growth on an airfoil up to stall. Further work with the IBL method has involved coupling with the LEWICE ice accretion code, as mentioned previously. An interesting result of this work is that the roughness parameters used in the ice accretion calculation were not the same values used in the viscous-flow drag calculation. There is some linkage between the role of ice roughness level in heat transfer and in boundary layer development. Further study is required to determine the influence of roughness on the ice growth process as well as on the iced airfoil boundary layer development.

Navier-Stokes calculations, while requiring more computer time, reveal interesting details of the iced airfoil aerodynamics not produced by the IBL method.

Potapczuk³⁴ has used the ARC2D code with a modified algebraic turbulence model to calculate the flowfield for the same iced NACA 0012 geometry that was used in the IBL calculations. Results, also shown in Figure 7, indicate good agreement with data even beyond the stall condition. The structure of the recirculation zone aft of the ice shape was also examined and compared to the measurements of Bragg,³⁵ as shown in Figure 8. These results reveal that the reverse flow velocity is not calculated properly. Use of a more appropriate grid or alteration of the turbulence model may be required. Additionally, results from investigations of Bragg and Khodadoust,³⁶ and Zaman and Potapczuk³⁷ suggest that there may be significant flow unsteadiness as this iced airfoil approaches stall.

The recirculation zone in the region aft of the ice shape results in complicated flow structures which are fundamentally three-dimensional in nature. An effort has begun to calculate the flowfield for a swept wing geometry with ice on the leading edge. Kwon and Sankar³⁸ have used a 3D Navier-Stokes code to evaluate the aerodynamics of a finite span wing model with a NACA 0012 profile and a 30° sweep angle. Figure 9 shows particle traces obtained from their calculation for an 8° angle of attack condition. The traces show the separated flow condition that occurs behind the ice shape and increases in size from the root to the tip of the wing. Their results for clean and iced conditions agree quite well with the experimental results of Khodadoust and Bragg.³⁹ Figure 10, which shows the comparison of spanwise lift distribution for these two conditions, supports the promising results from this simulation effort.

3.3 Ice Protection System Models

Ice protection systems have also been modeled computationally. Analysis methods for thermal systems are the most advanced. Both hot air systems and electrothermal systems have been modeled successfully. There have been fewer reported results from analysis efforts for mechanical systems. However, some recent activity in this area suggests that these systems will also be modeled computationally in the future.

Al-Khalil, et al.⁴⁰ used a 3D potential flow code, a 3D particle trajectory code, and a control volume energy analysis to evaluate a hot air anti-icing system for an engine inlet. This method holds the potential for optimization of hot air ice protection systems.

Electrothermal systems have been modeled using finite-difference methods by Keith, et al.⁴¹ An electrothermal system consists of an array of electric heater elements embedded under the outer skin of the wing surface. The heater elements are activated during an icing encounter with enough current to melt the ice that may form on a wing surface. A typical 2D model of an

electrothermal heater element is shown in Figure 11. The model simulates the thermal behavior of the composite structure and ice layer. Results indicate that temperature traces at the ice-skin interface, heater base, and substrate base agree well with measured values. Current work by Wright, et al.⁴² in this area is centered on combining this analysis with ice accretion predictions in order to provide a tool for the evaluation of electrothermal anti-/de-icing system performance.

Development of methods for evaluation of mechanical ice protection systems is just beginning with some initial work on ice structural properties described in References 43-45. Computational methods to predict FOD (*i.e.* shed ice) damage to engine blades are also under development. The ability to determine the damage resulting from various sizes and shapes of shed ice will greatly enhance de-icing system design.

A mechanical system that has been evaluated computationally is the Pneumatic Impulse Ice Protection (PIIP) system. The PIIP system relies on rapid inflation of pneumatic tubes embedded the wing surface.⁴⁶ The pneumatic impulse causes a displacement of the surface which combined with the surface acceleration, cracks, debonds, and expels the ice. Ramamurthy, et al.⁴⁷ used a time dependent, compressible flow model for internal duct flow to model this ice protection system. Results to date have been encouraging however further work is required.

4. Experimental Simulation Methods

The remainder of this paper will discuss approaches to experimental icing simulation, a topic that includes both experimental facilities and the testing done in them. The prevalent approaches are as follows:

- testing in icing wind tunnels;
- testing in engine test cells that can produce supercooled clouds;
- testing in outdoor ground-level spray facilities that can produce supercooled clouds during the winter;
- testing in environmental chambers that can produce subfreezing air temperatures and supercooled clouds;
- flight testing behind aircraft spray tankers equipped with water tanks and spray booms to produce supercooled clouds; and
- testing with replicated or simulated ice shapes.

References which contain comprehensive surveys of all icing facilities in Europe and North America, and

brief descriptions of three new icing wind tunnels in North America are contained in section 4.1.3.

Principal applications of experimental icing simulation include testing of full-scale and sub-scale aircraft components, developing advanced ice protection systems, conducting basic research on the icing process and on the fundamental properties of ice, establishing empirical data bases and correlations, and developing and validating analytical models or computer codes.

4.1 Icing Simulation Facilities

The need to produce both repeatable and predictable icing test conditions for the evaluation of computer codes and ice protection systems, has led to the development of specialized icing test facilities. The following discussion centers on the requirements for and issues surrounding facilities designed to simulate the natural icing environment under controlled test conditions.

4.1.1 Icing Wind Tunnels and Test Cells

Icing wind tunnels and engine test cells undoubtedly offer the most versatile approaches to icing testing. It generally costs much less to test components in an icing wind tunnel than in flight, and conditions can be much more closely controlled and repeated. In icing tunnel testing, productivity is high and the safety risk is very low. But there definitely is an appropriate role for flight testing, and that role will be discussed later.

A schematic of the closed-loop NASA Icing Research Tunnel (IRT) is shown in Figure 12. In addition to having all the systems of a conventional dry air tunnel, an icing tunnel has two unique systems: a water spray system that injects water droplets into the airstream to create a supercooled cloud and a refrigeration system and heat exchanger that cools the air to temperatures as low as minus 30°F. The heat exchanger is in the leg just upstream of the spray bars. Closed-loop refrigerated tunnels can "dial in the weather" any time of the year and are therefore very productive. For example, in 1988, the NASA IRT logged 1330 hours of test time, making it one of NASA's most productive tunnels.

Some icing tunnels bring in subfreezing outside air to supply the cooling. Since they are restricted to operating only in the winter, their productivity is lower, and it is much harder to achieve a systematic and reproducible test program in them.

The heat exchanger and spray systems in icing wind tunnels introduce unique operational challenges. First, the air temperature and velocity profiles must remain uniform across the test section for the several hours that tests usually require, even though as time progresses the heat exchanger surfaces capture and freeze out the water injected by the spray system. Second, the cloud must be uniform over the test section. Third, the cloud must con-

sist of supercooled droplets and no ice particles. Fourth, the spray system must be capable of reproducing nature's wide range of liquid water contents, droplet size spectra, and droplet median volumetric diameters (MVD). MVD is defined as the diameter where half of the volume of water is contained in droplets with diameters smaller (or larger) than this diameter. And fifth, the icing cloud and air temperature must be repeatable and controllable to within fairly close tolerances. In practice, no icing tunnel fully meets these requirements, but good tunnels do a reasonable job of approximating them.⁴⁸

Another critical challenge for icing tunnels is the accurate measurement of the supercooled cloud properties. LWC can be measured to within about ± 10 percent. But the accuracy of droplet sizing instruments is not known precisely, and inaccuracies greater than ± 2 microns are probably typical for MVD's from 10 to 40 microns.⁴⁹ Finally, methods to detect ice particles in a cloud are primitive, and methods of quantifying the amount of ice in a cloud are not yet available.⁵⁰

Engine test cells are used to evaluate the ice accretion patterns that may develop on engine inlets, to investigate the effects of the icing environment on engine operations and performance, and to evaluate the performance of engine ice protection systems. Engine test facilities are of two types: sea-level test stands and altitude test cells. The former having the advantage of large size and the ability to examine crosswind icing, while the latter has the advantage of being able to test over a wide range of Mach numbers, pressure altitudes, and inlet conditions without regard to prevailing weather.

The General Electric icing test facility in Peebles, Ohio, is an outdoor engine test stand located downstream of a large, free jet wind tunnel. A schematic of the facility, taken from Reference 51, is shown in Figure 13. The facility has been used to test the icing characteristics of several full-scale engines. The facility is designed to produce supercooled water droplets of 15 to 50 micron diameter at LWC levels ranging from 0.4 to 3.6 g/m³. The facility is also designed to produce these conditions at temperatures of -20° to 0° C. The temperature conditions are of course dependent on the ambient temperature.

The lack of altitude pressure capabilities for this facility necessitates the development of adjustments to engine variables or to test variables such as LWC, drop size, and liquid/air mass flow ratios in order to simulate flight conditions. The facility is also limited to humidity conditions prevalent in the atmosphere during the scheduled test period. In order to increase the number of test opportunities available in this facility a set of scaling laws would be useful in order to adjust controllable parameters, thus allowing simulation of alternate flight conditions.

Altitude test facilities provide the capability to perform engine icing tests under conditions similar to those experienced in-flight. Examples of altitude icing facilities are the AEDC Engine Icing Test Facility at Tullahoma, Tennessee, USA;⁵² the icing test cells at the National Gas Turbine Establishment (NGTE) at Pyestock, UK;⁵³ and the Centre d'Essais des Propulseurs (CEPr) at Orsay, France.⁵⁴ A schematic of the free jet icing test cell at AEDC, taken from Reference 52, is shown in Figure 14. This arrangement is typical of the engine icing test cells.

Testing in altitude test cells generally consists of determination of ice accretion patterns on engine component surfaces, ice protection system evaluation, and engine icing damage assessment. Since the engine models used in such facilities are generally not full-scale, the question of scaling plays a predominant role in determining test conditions. Typically, all the scaling parameters necessary for complete similitude cannot be satisfied during a single test. Hence, there is a need to develop test programs to evaluate the relative importance of scaling parameters in order to relax some of the constraints on engine icing tests. Ruff⁵⁵ and Bartlett⁵⁶ provide a more detailed discussion of similitude for engine icing tests.

4.1.2 In-flight Icing Simulators - Spray Tankers

Although computer simulations and icing tunnel testing are important steps in an icing program and hold the promise for an increased role in the future, flight testing of the full-scale aircraft is still an essential step in achieving icing certification or qualification. Before launching into an extensive flight test program in natural icing, it is sometimes advantageous to precede flights in natural icing with flights behind a spray tanker.

Icing flight testing behind a spray tanker offers important benefits: first, it offers a safety advantage because the pilot can fly the test aircraft out of the cloud and terminate the test if he encounters any problems; second, it can save development time and costs by providing cloud conditions that rarely occur in nature, yet are conditions in which the aircraft must be certified or qualified (such as higher LWC's or larger MVD's); and third, it serves to uncover major equipment problems that should be fixed before undertaking an extensive, expensive, and high risk flight test program in natural icing.

Producing a supercooled cloud with an in-flight spray tanker and calibrating that cloud presents all the challenges found in an icing tunnel plus some others. For example, the outside air humidity profoundly affects the cloud droplet size. Dryer air causes the smaller droplets to evaporate, and since any humidity from zero to 100 percent is possible on any flight, it is difficult or impossible to achieve predetermined MVD's or LWC's. Thus, before each immersion of the test aircraft in the cloud,

another aircraft equipped with cloud instruments must fly through the cloud to measure its conditions. A further challenge for tanker spray systems is to provide the copious supplies of high pressure air required by the nozzles to produce the smaller droplets typically found in nature (10 to 40 microns MVD). Or conversely, the challenge is to develop a nozzle that can produce the smaller droplets with lower air pressures and flows. Nozzle research for the special needs of the spray tankers is ongoing.⁵⁷ If nozzles are developed that make small droplets with lower air pressures and flows, they will also be advantageous for wind tunnels and engine test cells, because lower nozzle air pressures will result in less droplet freeze-out.

Some of the general aviation airplane manufacturers use one of their own aircraft as a spray tanker, but the two best known spray tankers in the United States belong to the military: the Air Force's KC 135 spray tanker and the U.S. Army's Helicopter Icing Spray System (HISS).

The Air Force's spray tanker is a KC-135 aircraft equipped with a 2000 gallon water tank and a new square spray boom that extends below the aircraft's tail. The test aircraft flies 50 to 100 feet behind the boom, and depending upon the distance behind the boom, the cloud size ranges from about 5 to 10 feet square. Most testing is done at aircraft speeds from 150 kt to 300 kt indicated. The tanker is used primarily for icing tests of engines, but it is also used for tests of windshields, control surfaces, missile/aircraft interface launches, missiles, and radomes.

The Army's HISS tanker is a Boeing Chinook CH 47 D helicopter that carries an 1800 gallon water tank and a rectangular spray boom that drops down below the Chinook after the ship is airborne. The test aircraft flies about 180 feet behind the boom, where the cloud size is approximately 8 feet high by 36 feet wide. Most testing is done at aircraft speeds from 80 to 130 kt true. The HISS is used for testing both helicopters and low-speed fixed-wing aircraft.⁵⁸ Typical tests for helicopters include main rotors, tail rotors, engine inlets, fuselages, stabilators, droop stops, windshields, antennas, external stores, airspeed sensors, production ice detectors, optical system sensors (pilot night vision, and target data acquisition), refueling booms, external hoists, and various mission equipment exposed to the airstream.

As part of an overall program to assess Army and NASA cloud measurement systems, NASA flew their Twin Otter icing research aircraft behind the HISS⁵⁹ in order to acquire main wing ice shape and drag data for clouds with large MVD's, a condition that is rare in natural icing around the Great Lakes area where the Twin Otter is stationed. Figure 15 shows main wing ice shapes and drag values for two different conditions;⁶⁰ first, a flight in natural icing with a 16 micron MVD cloud, and

second a flight behind the HISS with a 35 micron MVD cloud. The HISS cloud, with the larger drop size, produced a greater extent of ice coverage and a wing section drag coefficient about 25 percent higher.

4.1.3 Surveys of Icing Simulation Facilities

Many aircraft icing simulation facilities exist worldwide. In 1981, Olsen⁶¹ published a survey of icing simulation facilities in North America. Two excellent surveys of these facilities are listed in AGARD References 62, and 63. AGARD AR-166, surveyed all the facilities in Europe and North America as of 1981. In 1986, AGARD AR-223 amended the earlier AR-166 to delete those facilities removed from service and to add new facilities developed since 1981.

In February 1991, the Society for Automotive Engineers (SAE) sent panel members of the SAE AC-9C Activity AC-9C-90-1 a questionnaire intended to obtain a comprehensive description of all aircraft icing facilities in Europe and North America. One goal of the survey is to determine how facilities are presently calibrated. The activity also has a goal to determine if some reliable and easily performed calibration methods could be established that would allow all facilities to be compared on a common basis.

Since 1986, three new facilities were added in the United States. Fluidyne in Minneapolis, Minnesota, USA, modified a transonic wind tunnel to include an icing spray system.⁶⁴ The tunnel uses outside air during the winter to obtain the subfreezing temperatures. The test section is 22 in. x 22 in., with Mach numbers up to 0.8. This tunnel offers the potential for obtaining ice shapes and aeroperformance data on full-scale helicopter rotor blade sections.

The BFGoodrich Deicing Systems Group in Uniontown, Ohio, USA, brought on line in 1989, a new icing tunnel.⁶⁵ The test section is 22 in. x 44 in., with airspeeds up to 200 mph. This facility also includes a cold room that allows researchers to move icing samples from the test section to the cold room where they can be stored or studied further.

The Boeing Mechanical Systems Laboratory in Seattle, Washington, USA, is bringing on line the Boeing Research Aerodynamic/Icing Tunnel (BRAIT). The BRAIT will have three test section sizes: 5 ft x 8 ft (150 kt max airspeed), 4 ft x 6 ft (250 kt max airspeed), and 2.4 ft x 4.4 ft (350 kt max airspeed). The spray system will be removable for dry air testing. The tunnel is scheduled to begin testing in March 1992. Boeing estimates that the use of their new tunnel will save them up to one million dollars for each new airplane they certify for icing.

4.2 Icing Testing Techniques

Icing testing can be performed in facilities such as those described above and in addition can be done in conventional facilities such as dry air wind tunnels. In this section, several types of test programs will be described in order to illustrate the range of experimental methods used to understand the icing process and to demonstrate the efficacy of ice protection systems.

4.2.1 Ice Accretion Physics

Icing tunnels are a good place to study the fundamental processes of ice accretion because they control and repeat conditions quite well. As mentioned previously, Olsen and Walker¹⁰ observed the icing process in the NASA IRT with close-up movies. These movies revealed accretion phenomena for glaze ice quite different from that contained in the currently used analytical model for ice accretion. These differences were discussed in the analysis section above.

In addition to the close-up movies, Olsen examined the structure of the ice deposits, the effect of ice shape on droplet catch, ice roughness effects, the effect of initial surface flow on the resulting ice shape, and the effect of droplet shedding. Olsen also discussed the use of plastic replicas of the ice shapes, developed during previous testing,⁶⁶ to evaluate the local heat transfer coefficient in a dry air wind tunnel. This illustrates the inter-relationship between testing in an icing facility and in a dry air wind tunnel. The techniques used in Olsen's test program illustrate the type of information relating to ice accretion physics which may be obtained in an icing test facility.

Personne⁶⁷ examined the effects of roughness on the type of ice developed on cylinders. He found that for low airspeeds (less than 20 m/s) surface roughness increases the droplet collection efficiency. He also suggests that rime ice roughness levels are due to the random nature of droplet trajectories caused by increased airstream turbulence near the surface.

4.2.2 Icing Effects on Aeroperformance

An important aspect of icing simulation is the experimental measurement and analytical prediction of ice accretions and their effects on wing aerodynamics. The combined use of icing wind tunnels and conventional dry air tunnels has proven effective in studying the effects of ice on airfoil aeroperformance. When conventional tunnels are employed to study icing effects, the ice is simulated by attaching a replica of an ice shape to the airfoil's leading edge. Ice replicas are obtained by several methods as discussed below.

The best method for obtaining detailed replicas of leading edge ice is from silicone rubber molds, which replicate both the ice shape and its surface texture.⁶⁸ Once the female mold is made, epoxy resin is poured into

the mold to form a casting of the ice. In a second method, chordwise cross sections of the ice are obtained by melting a thin cut in the ice around the leading edge, inserting a template in the cut, and drawing an outline of the ice on the template. A third method uses mono or stereographic photos to obtain ice shapes.

Ice replicas are typically made from wood, styro-foam, or epoxy resin. Sometimes the airfoil is machined or molded to coordinates that include the shape of the leading edge ice. Unless the surface texture is obtained from silicone rubber molds, some method of adding surface roughness is needed. Roughness can be added for example, by applying sand grain or by roughing up the surface with a knurling tool.

Ice replicas are used in conventional wind tunnels for several reasons: (1) the icing tunnel in which the ice was formed may not have the necessary force balances or flow quality to make good aerodynamic measurements; (2) making pressure measurements in a cold, moist cloud environment doesn't work well; (3) real ice sublimates, and sometimes rust or dirt circulating in the tunnel erodes the ice, so unless the aerodynamic measurements are done quickly, the ice shape and surface roughness will change during the tests; (4) ice replicas allow the test to be repeated as many times as necessary to get good aeroperformance data; and (5) in the case where the experimental aeroperformance data base is to be used for code validation, ice replicas machined or molded to precise coordinates on an airfoil will allow the flow codes to model the exact airfoil shape used in the wind tunnel test.

As part of their landmark study of icing and its aerodynamic effects, the Swedish-Soviet Working Group on Flight Safety conducted testing in a Soviet icing tunnel and a Swedish dry air tunnel to study the effects of wing and tail ice on aircraft stability. In one study, they tested several configurations of a 2D, four-element wing section (1 m chord), including advanced high-lift devices.¹⁵ And in another study, they tested two swept tailplane configurations with flaps.⁶⁹ The airfoils were tested in the Special Wind Tunnel T-4 at the Research Institute of the Ministry of Civil Aviation, USSR. The tunnel cross section was 1.5 x 2.0 m, and its speed range was 10 to 70 m/s. The tunnel was equipped with a spray system and used outside air below 0°C for cooling. In setting the tunnel icing conditions, the Soviets applied approximate icing scaling relations to relate model test conditions to full-scale conditions. Very detailed female silicone rubber molds were made of the ice accretions. In Sweden, the molds were attached to airfoils, and epoxy resin was poured into the molds to form detailed replicas of the ice shapes. The airfoils with the ice replicas were then tested in the 3.6m diameter FFA conventional dry air wind tunnel in Sweden. These dry air tunnel tests produced a comprehensive set of curves of lift, drag, and moment for

several angles of attack up to and beyond stall, and for various flap and slat configurations. The Working Group also reported results where they used emery paper to simulate frost ($k/c = 1/1300$) in the conventional wind tunnel tests. Figure 16, taken from Reference 15, shows the effect on $C_L(\alpha)$ and $C_{L,max}$ of ice shapes corresponding to icing in cruise but with trailing edge flaps extended.

Olsen,⁷⁰ in a comprehensive study in the NASA IRT, systematically varied key icing tunnel and cloud parameters to obtain a series of ice shapes and resulting drag coefficients for a NACA 0012, 21 in. chord airfoil (Figure 17). Recently, Olsen's data was compared with predictions made by a version of LEWICE modified to include the interactive boundary layer (IBL) method that predicts lift, drag, and pitching moment of the iced airfoil.²⁹ The experimental data used in the IBL/LEWICE comparisons were from runs made at several air temperatures, while holding cloud conditions and airspeed constant. As revealed in Figure 18, air temperature strongly affects ice shape and its resultant drag, especially just below the freezing point. Figure 6 compares the IBL/LEWICE predictions with the temperature sweeps.

Potapczuk and Berkowitz¹⁶ tested a 2D, five-element airfoil, in four different configurations (Figure 19), in the NASA IRT. The airfoil was a two-dimensional section of the Boeing 737-200 ADV aircraft wing that Boeing had used earlier as part of their ground de/anti-icing fluids evaluation in the NASA IRT. The airfoil was mounted between two splitter walls, each of which contained a turntable for varying the angle of attack and a force balance for measuring lift, drag, and pitching moments. Performance characteristics were measured at a given angle of attack during the ice accretion process and then over a range of angle of attack conditions after the accretion process was complete. All test equipment, including the data acquisition systems, were provided by Boeing.

Their results indicate the change in stall mechanism that can occur due to the presence of ice on leading edge surfaces. As seen in Figure 20, the C_L vs. α curve has a much lower $C_{L,max}$ value and the slope of the curve beyond $C_{L,max}$ changes dramatically. These differences suggest a change from trailing edge stall to leading edge stall. Changes of this sort can remain undetected at cruise conditions, yet could cause severe problems during take-off or landing.

Flemming³² tested several modern helicopter airfoils in the National Research Council's icing tunnel in Ottawa, Canada. The chord of the airfoils was about 6 in. Silicon rubber molds were made for many of the ice shapes. The NRC tunnel was chosen because it could be run to about Mach 0.7, which is representative of the Mach numbers near the tip of a helicopter rotor. Flem-

ming used the data to develop an empirical correlation for lift, drag, and pitching moment changes caused by icing. He has used these results in the Sikorsky Generalized Rotor Performance Code (GRP) to predict full-scale helicopter torque rises and lift loss, and more recently has used the correlations, with some modifications, to predict the performance of a sub-scale model rotor that was tested in the NASA IRT.⁷¹ These sub-scale model rotor tests are described in a recent report by Fleming.⁷²

The aerodynamics of modern swept wing aircraft is dominated by three dimensional effects. As mentioned earlier, NASA is developing 3D flow codes that can model the flow over swept, finite length wings with leading edge ice. To validate the flow codes, NASA has sponsored a parallel experimental program in a dry air wind tunnel⁷³ to obtain a comprehensive data base on the aeroperformance of swept, finite length wings with ice replicas on the leading edge. Figure 21 shows a 30° swept wing model in a dry air wind tunnel. The ice replica can be seen in the edge-on view. The wind tunnel has the ability to remove the boundary layer through side-wall suction at the wing root. The model is heavily instrumented for surface pressures and is attached to a three component force balance in the wind tunnel wall. Flow diagnostics include laser velocimetry and helium bubble seeding and tracking. Some typical results from this effort were discussed earlier in section 3.2.

4.2.3 Ice Protection Systems Testing

Icing tunnels are used to develop and test aircraft ice protection systems, which include pneumatic boot deicers, porous leading edge fluid deicers, electrothermal deicers, electrothermal evaporative and running-wet anti-icers, hot air evaporative anti-icers, pneumatic impulse deicers, and electro-mechanical impulse deicers. These systems apply to wings, tails, rotor blades, propellers, and engine inlets.

When considering new ice protection systems, airframers are looking for systems that offer some, or all, of the following improvements: lower weight; lower power consumption; acceptable aero-penalties that in some cases may require ice thicknesses not to exceed 0.040 in.; more reliable operation; lower maintenance time and costs; easily retrofitted to existing components; not dependent on compressor bleed air; and more economical to manufacture.

4.2.3.1 Mechanical Impulse Deicers

In their search for alternatives to compressor bleed air and energy-intensive electrothermal anti-icing systems, airframers are considering the pneumatic impulse and electro-mechanical impulse deicer systems now under early development by the ice protection system

manufacturers.^{46, 74-76} Impulse systems have pulse times less than a millisecond and surface accelerations up to 1000 g's, imparting forces strong enough to shatter, debond, and expel the ice. The impulse systems require minimal power (i.e. on the order of the aircraft's landing light power) and they have the potential for maintaining ice thicknesses very thin, both before and after actuation.

In testing impulse deicers the following parameters are measured to characterize deicer performance: (1) maximum size of shed ice particles for a given ice thickness and pulse energy; (2) minimum thickness of ice that can be removed for a given pulse energy; (3) amount, texture, and height of residual ice remaining on the surface before and after deicer actuation; (4) energy per unit area or per unit span length required for one deicer actuation; and (5) weight per unit area of deicer coverage.⁷⁶

In evaluating deicer performance, the systems must be tested under the full range of expected icing conditions. Experience has shown that two conditions give impulse deicers the most trouble: near-freezing conditions that produce soft, mushy ice with water between the ice and deicer surface; and cold, rime icing conditions that cause the ice to adhere strongly to the deicer surface.^{75, 77} Knowledge of shed ice size would be essential if a deicer were to be used on a jet engine inlet, because engine fan blades would be damaged if the engine were to ingest ice particles greater than a prescribed size as determined by the engine manufacturer.

Power usage is so low for any these impulse systems that airframers compare them primarily on the basis of weight, complexity, ease of installation, maintainability, and aerodynamic penalties caused by the system installation and by the surface ice before and after deicer actuation.

Figure 22 contains a sequence of photos, from recent low power de-icing tests in the NASA IRT,⁷⁷ that capture an ice shedding event by means of high speed videography. Events can be captured at speeds up to 6000 frames per second on special video tapes. These tapes can be examined frame by frame with motion analysis software coupled to a micro-computer. This allows the size of the largest particles shed during an actuation to be estimated and the ice breakup process in the airstream to be followed. Special image processing software is being developed to automate the estimation of particle sizes and possibly to obtain size spectrums as well.

4.2.3.2 Water Runback in Thermal Ice Protection

Thermal deicers or anti-icers are still the most prevalent types of ice protection systems used on aircraft. If these systems are overwhelmed in severe icing, or if in the case of deicers, their on/off timing sequences are improperly adjusted, water in the form of rivulets can run back beyond the heaters and refreeze. Enough runback

water could accumulate over time to cause aerodynamic performance or stability problems, or ice could shed and be swept downstream to damage aircraft or engine components. Thus, ice protection manufacturers are beginning to develop water runback and refreeze models for their ice protection analysis and design codes. For example, see Reference 78 for runback modeling of hot bleed air anti-icers. There does not appear to be extensive experimental icing data for use in validating the runback models, but more work on development of this database is planned.

4.2.3.3 Heat and Mass Transfer from Wet Surfaces

Thermal anti-icers evaporate water that impinges on the airfoil leading edge. In general, impinging droplets are not evaporated immediately upon impact, but rather the water forms a thin film that is heated and evaporated in the process of flowing downstream along the heated surface. Heat transfer correlations for air flowing over dry airfoil surfaces are readily available to the manufacturers, but correlations for heat and mass transfer over wet airfoil surfaces are not adequate. This is an area where experimental research is still required to support validation of computer models for evaporative anti-icing systems.

4.2.4 Special Techniques for Rotorcraft

Only one civilian helicopter, the French Super Puma, is certified in the United States for flight into forecasted icing conditions. It took approximately ten years of flight testing in natural icing to receive the FAA's certification.

The U.S. rotorcraft industry estimates that, if flight testing in natural icing is the only acceptable means for certification, it would cost about 15 million dollars to certify a helicopter to the full FAA, Part 25, Appendix C criteria. This cost is prohibitively high.

For several years, NASA and the U.S. rotorcraft industry have been engaged in a joint effort to develop new methods of reducing the cost and time needed to certify and qualify U.S. rotorcraft for icing.

These methods include (1) computer codes that reliably predict full-scale rotor performance in icing and (2) experimental techniques for testing sub-scale model helicopter rotors in the IRT to acquire data for validating the codes and to develop a better understanding of the effects of icing on rotor performance.

The methods derived from these studies will also advance the state-of-the-art for predicting the effects of ice accretion and shedding for the advanced ducted propellers and other thrusting devices.

4.2.4.1 Sub-scale Model Rotor Testing in Icing Wind Tunnel

Figure 23 shows a sub-scale helicopter model being tested in the IRT. The model consists of a helicopter fuselage, four NACA 0012 blades (4.9-in. chord, 6-ft diam.), a fully articulated rotor head, and a six-component force balance housed under the fuselage.^{71,72}

Some results from the sub-scale model rotor testing are shown in Figure 24. This figure shows the torque rise caused by ice accretion on the rotors versus time in icing. The experimental results are compared with an analytical prediction developed by Flemming⁷² that includes an ice shedding model. The analytical prediction includes empirical airfoil performance-in-icing data that was acquired in previous tests.³² The comparison between analysis and experiment, as shown here, was remarkably good for this particular test run. Similar agreement was also found between analysis and experiment for lift loss versus time in icing.

Another approach to sub-scale model rotor testing would involve the use of simulated ice applied to the leading edge of the rotor blades. The rotor blades with the simulated ice would be tested in a dry wind tunnel. The key to successful dry air wind tunnel testing with simulated ice would be having the correct ice shapes, with appropriate roughness, properly located on the blades. The appropriate simulated ice would be obtained from scale model testing in an icing tunnel, or from predictions with ice accretion codes. It is unlikely that sufficiently accurate ice shapes could be acquired from full-scale helicopter flights in natural icing conditions because the ice erodes and sublimates substantially during the time it takes to descend, land, and shut down.

4.2.4.2 Ice Shedding from Rotor Blades

An important problem for propellers and helicopter rotors is shedding of ice from their tips where centrifugal forces can exceed 1000 g's. When multiple rotor blades shed ice asymmetrically, the resulting imbalances cause vibrations severe enough to prevent the pilot from reading his instruments. Another concern is that shed ice particles have considerable energy and can damage aircraft structures. For example, in the design of the tilt rotor aircraft, the fuselage was covered with armor plate in those areas where ice would impact. This armor plate added a severe weight penalty.

Rigorous analytical models and supporting experimental data are needed to predict (1) shed ice events and the size of the shed ice, (2) shed ice trajectories, (3) impact energy of the ice particle and (4) structural damage caused by ice impact. A current project at NASA Lewis is attempting to address some of these issues.

4.2.5 Flight Testing with Simulated Ice Shapes

Icing flight testing with simulated ice shapes on selected lifting surfaces is done as part of the process of obtaining icing certification or qualification, or it is done to acquire a data base for use in validating computer codes that predict overall aircraft performance and stability in icing.

If ice replicas are used on lifting surfaces during flight testing as part of the process of obtaining icing certification or qualification, then the following important caution from Reference 15 must be heeded: '...It has been found that the shape of the ice deposit on an airfoil plays the main role in worsening of the aerodynamic characteristics. Flight experiments have shown that even a thin layer of ice might have a serious influence. On the other hand, cases are possible when a thick ice deposit has no significant influence on the flying characteristics...'. Therefore, when simulated ice is used in flight testing, the selection of ice shapes is critical. Ideally, it would be desirable if computer codes that predict ice shapes and resulting aeroperformance and stability could be used to judiciously select ice shapes. But until these codes have been extensively validated, which will take many years, certification testing will still depend critically on flight testing in natural icing, with the aircraft in its various multi-element wing and tail configurations. When simulated ice is used, the ice shapes should be based on extensive icing flight test experience.

In the certification process, aircraft are ordinarily tested with simulated ice shapes for two prominent reasons. First, in the event of an ice protection failure, the airplane will accrete ice that could degrade aircraft performance and stability. Thus, the airframer may elect to use simulated ice to demonstrate flight safety in the event of ice protection failure. A second reason for using simulated ice would be when an airframer deliberately chose not to protect a given component. Then the airframer would have to prove that the aircraft could fly safely with ice on the unprotected surface. They could then elect to use simulated ice to demonstrate flight safety.

As mentioned earlier, newer commercial transports are powered by advanced turbofan engines with higher bypass ratios and smaller core flows. So airframers are taking a close look at whether ice protection can be safely eliminated from certain aircraft components in order to conserve on bleed air usage.

Even in the past when commercial jet transports had copious supplies of bleed air, airframers examined the advantages and disadvantages of protecting certain components from ice, especially vertical tails. By making an unprotected vertical tail large enough, airframers could achieve acceptable tail aerodynamics for expected ice accretions. So airframers compared the amount of fuel required to carry a heavier tail against the fuel required

both to carry the extra weight of hot air ducting and to overcome the loss of engine power due to use of more engine bleed air.

As a recent example for an aircraft powered by high bypass engines, the Boeing 757 was the first commercial transport to be certified by the FAA without ice protection on the outboard leading edge slats. This need to identify specific components of an aircraft system and selectively remove unnecessary ice protection was driven by the reduction in available bleed air. In the process of acquiring the certification, Boeing first used replicated ice shapes on a sub-scale model of the 757 tested in a dry air wind tunnel. The stability and control characteristics were studied in the wind tunnel tests. Next, simulated ice shapes were attached to the actual aircraft's outboard slats, and the airplane was flown in clear air, again to study the effect of the ice on performance and stability. Finally, the airplane was flown in natural icing to complete the icing certification process. Relying on their vast experience in natural icing flight testing, Boeing was able to derive empirical and analytical methods to determine the most representative ice shapes for the simulation.

In a recent research program, NASA used replicated ice shapes on the horizontal and vertical tails of their Twin Otter icing research aircraft to study the effects of tail ice on stability and control (References 79 and 80). First the Twin Otter was flown in natural icing and photos were taken of the ice formations on the tail surfaces. From these photos, styrofoam shapes were fabricated and then attached to the tail surfaces (Figure 25). The aircraft was then flown in clear air through a series of maneuvers designed to acquire a flight data base for use in determining stability and control derivatives. The flight data was analyzed by a modified stepwise regression algorithm and a maximum likelihood algorithm that yielded estimates of body-axis stability and control derivatives related to the short-period, longitudinal motion of the aircraft.

As mentioned earlier, NASA is developing a computer flow code to predict performance and stability of modern aircraft with given ice shapes on the lifting surfaces. Estimated stability and control derivatives and performance measurements from the Twin Otter will be used to validate the code at full-scale Reynolds numbers. In addition to the Twin Otter flight testing with replicated ice shapes, dry air wind tunnel testing will be conducted of a sub-scale model of a modern swept wing aircraft with replicated ice on its lifting surfaces. The wind tunnel results will provide code validation data for a modern transport aircraft. After a good data base has been acquired from the wind tunnel testing, flight tests with a modern swept wing aircraft will be conducted to acquire a validation data base at full-scale Reynolds numbers.

As noted in Reference 80, 'the successful estimation of stability and control derivatives from flight data has two important ramifications. First, the values for the derivatives can be compared with values derived from the analytical icing codes and from the IRT. These comparisons allow for an assessment of the confidence that should be put in analytical predictions and wind-tunnel results as they relate to an aircraft in flight. Second, flight-derived derivatives can be used judiciously along with those provided by analytical predictions and wind tunnel tests to upgrade simulator math models to provide a realistic set of aerodynamics for pilot-in-the-loop simulations of icing scenarios.'

4.2.6 Icing Scaling

The proposed or desired test matrix for an icing test usually involves the following variables: airspeed, outside air temperature, altitude, cloud liquid water content, cloud droplet size distribution or median volume diameter, and model size or scale. In a flight test in natural icing or in an artificial cloud behind an in-flight spray tanker, chances are that the set of variables desired will be unattainable. In a wind tunnel test, certain combinations of variables also will be unattainable. For example, most icing wind tunnels have maximum airspeeds far below the speeds of modern transport or military aircraft. And due to the practical limits on nozzle turn-down ratios and nozzle droplet size ranges, several sets of nozzles would be required to achieve the full FAA Part 25 Appendix C operating envelopes over the full speed range of the tunnel.

If the desired test variables cannot be met, the experimenter must resort to some form of scaling or similitude. Various scaling objectives can be imagined for any particular icing test, such as: (1) a geometrically similar ice shape; (2) an equivalent drag or lift coefficient; (3) the same water flux distribution around the airfoil leading edge; (4) the same heat transfer results for a thermal ice protection system; (5) rime icing conditions (*i.e.*, all water must freeze immediately upon impact); and so on. Not all of these objectives can be met simultaneously and hence the experimenter may have to choose those most appropriate for the specific test program.

Scaling laws have always been used, but never rigorously validated.³² Flight testing in natural icing clouds will always be a required part of the certification/qualification process.

Reference 10 gives a good bibliography of the work done previously on scaling. Most of these works on scaling rely on an analysis of the ice accretion process described by Messinger.¹⁰ As mentioned earlier, more recent studies have revealed that the Messinger model does not reflect recent observations regarding the ice accretion process.

These new results have led Bilanin⁸¹ to formulate the scaling laws independently from any mathematical model of the icing process. He did this by applying the Buckingham pi theorem for similitude to the ice accretion problem. The pi theorem approach showed, for example, that the normalized thickness of the ice accreted on the airfoil is a function of 18 nondimensional groups. Although many of the groups can be satisfied in any scaling test, Mach, Reynolds and Weber numbers cannot all be satisfied in the same scaled test. He concluded that although competing physical effects do not in general allow a rigorous scaling methodology, an acceptable approximate scaling scheme may still be possible. Bilanin's work is continuing under NASA/FAA sponsorship.

Since rigorous scaling is not achievable, a different approach has been taken in experimental icing testing. Components are tested in conditions as close as possible to the desired conditions, or some partial scaling is used. Analytical methods are then used to predict the results of the test. The analytical methods are adjusted, if necessary, to bring the experimental results and predictions into agreement. Then the analytical methods are used to predict results for the desired conditions. This is essentially the same approach used in acquiring a data base for validating any analytical prediction. With intensified efforts to develop computer simulations of all key aspects of aircraft icing, the necessity of a prolonged experimental effort to develop and validate scaling relations may be diminished.

5. Concluding Remarks

From the preceding discussion, it is evident that aircraft icing simulations consist of three interrelated activities; analytical modeling, ground-based experiments, and flight testing. Analytical methods started as correlations of experimental data and have more recently turned to computer models based on first principles. Computer models have been doing a steadily better job of simulating the icing process and its effects. Current two-dimensional codes are being used in industry for the simulation of icing effects and for the evaluation of ice protection system effectiveness. Three-dimensional methods are currently under development and hold the promise of accurately simulating an icing encounter for a complete aircraft configuration. Ground testing in icing wind tunnels, icing test cells, and dry air wind tunnels provides (1) simulations of conditions not yet capable of being modeled correctly, (2) safer and less expensive means of testing than in-flight testing, (3) controlled, repeatable experiments at known icing conditions, and (4) a data-base for computer code validation. The increasing number of these facilities in the industry attests to their

importance in developing effective ice protection measures for all types of aircraft. Finally, flight testing provides a means of determining the effects of icing on complete aircraft configurations and an essential check on the fidelity of the analytical and experimental simulation methods.

The future of icing simulation is tied to this three prong approach. It is important to understand that the advancement of either analytical or experimental simulation methods will always require the need of flight test data for verification purposes. The acceptance of simulation tools by aircraft designers and certification authorities will depend on the icing modelers ability to show the accuracy of simulation methods. Additionally, the interaction of modeler, experimentalist, and pilot can lead to a more realistic and therefore more useful simulation tool.

This paper has highlighted some of the recent developments in aircraft icing simulation. Several areas requiring further research have been identified. Some of these are:

- Ice accretion physics, specifically roughness characterization, heat transfer correlations, splashing, runback, surface tension effects, and wetting characteristics.
- Ice structural properties and ice shedding.
- Stall mechanisms and post-stall behavior of iced wings. Computational simulation of these phenomena.
- Inclusion of surface roughness effects in aerodynamics codes.
- Evaluation of turbulent flow properties for iced wings and development of appropriate turbulence models.
- Three-dimensional ice accretion code development.
- Computer code simulation of iced wing and iced aircraft performance. Development of performance codes for rotorcraft in icing.
- Development of computational methods for simulating ice protection systems.
- Continued development of experimental methods for simulating rotorcraft performance in icing.
- Creation and verification of icing scaling laws.

Certainly the continued development of the icing simulation methods described in this paper will continue to present an exciting challenge to the aerospace community for some years to come.

References

- 1) Anon., "National Aircraft Icing Technology Plan," Federal Coordinator for Meteorological Services and Supporting Research, FCM-P20-1986, U.S. Dept. of Commerce, April 1986.
- 2) Reinmann, J.J., Shaw, R.J., and Ranaudo, R.J., "NASA's Program on Icing Research and Technology," NASA TM-101989, presented at Symposium on Flight in Adverse Environmental Conditions, Gol, Norway, May 8-12, 1989.
- 3) Carroll, T.C. and McAvoy, W.H., "Formation of Ice on Airplanes," *Airway Age*, Sept. 1928, pp. 58-59.
- 4) Bleeker, W., "Einige Bemerkungen u ber Eisanzatz an Flugzeugen", *Meteorologische Zeitschrift*, Sept. 1932, pp. 349-354 (also available as NACA TM No. 1027).
- 5) Jacobs, E.N., "Airfoil Section Characteristics as Affected by Protuberances", NACA Report No. 446, 1932.
- 6) Jones, R. and Williams, D.H., "The Effect of Surface Roughness on the Characteristics of the Aerofoils NACA 0012 and RAF 34", *British ARC, R&M No. 1708*, 1936.
- 7) Gulick, B.G., "Effects of Simulated Ice Formation on the Aerodynamic Characteristics of an Airfoil", NACA WR L-292, 1938.
- 8) Comite d' Etude du Givrage Rapport du Mai 1938, *Bulletin des Services Techniques No. 85*, Publications Scientifiques et Techniques du Ministere de l' Air (also available as NACA TM No. 919).
- 9) Anon., "Selected Bibliography of NACA-NASA Aircraft Icing Publications," NASA TM-81651, NASA Lewis Research Center, Cleveland, OH, August 1981.
- 10) Messinger, B.L., "Equilibrium Temperature of an Unheated Icing Surface as a Function of Airspeed," *Journal of the Aeronautical Sciences*, Vol. 20, No. 1, 1953, pp. 29-42.
- 11) Olsen, W.A. and Walker, E., "Experimental Evidence for Modifying the Current Physical Model for Ice Accretion on Aircraft Surfaces," NASA TM-87184, May 1986.

- 12) Bilanin, A.J., "Proposed Modifications to Ice Accretion/Icing Scaling Theory," AIAA Paper 88-0203, Jan. 1988.
- 13) Hansman, J.R., and Turnock, S.R., "Investigation of Microphysical Factors Which Influence Surface Roughness During Glaze Ice Accretion," Fourth International Conference on Atmospheric Icing of Structures, Paris, France, Sep. 1988.
- 14) Hansman, J.R., Yamaguchi, K., and Berkowitz, B., "Modeling of Surface Roughness Effects on Glaze Ice Accretion," AIAA Paper 89-0734, Jan. 1989.
- 15) Ingelman-Sundberg, M., Trunov, O.K., and Ivaniko, A., "Methods for Prediction of the Influence of Ice on Aircraft Flying Characteristics," Swedish-Soviet Working Group on Flight Safety, Joint Report No. JR-1, 1977.
- 16) Potapczuk, M.G. and Berkowitz, B.M., "An Experimental Investigation of Multi-Element Airfoil Ice Accretion and Resulting Performance Degradation," NASA TM-101441, Jan. 1989.
- 17) Bond, T.H., Flemming, R.J., and Britton, R.K., "Icing Tests of a Sub-Scale Model Main Rotor," Proceedings of the 46th Annual American Helicopter Society Forum, May 1990, pp. 267-281.
- 18) Negrette, A., "The Pilot's Responsibility in Icing Conditions," Rotor and Wing International, Vol. 25, No. 1, Jan. 1991, pp. 98-99.
- 19) Shaw, R.J., Potapczuk, M.G., and Bidwell, C.S., "Predictions of Airfoil Aerodynamic Performance Degradation Due to Icing," Numerical and Physical Aspects of Aerodynamic Flows IV, Springer-Verlag, Berlin, 1990, pp. 19-35.
- 20) Lozowski, E.P. and Oleskiw, M.M., "Computer Modeling of Time-Dependent Rime Icing in the Atmosphere," CRREL Report 83-2, USAF, Jan. 1983.
- 21) Ruff, G.A. and Berkowitz, B.M., "Users Manual for the NASA Lewis Ice Accretion Prediction Code (LEWICE)," NASA CR-185129, May 1990.
- 22) Cansdale, J.T. and Gent, R.W., "Ice Accretion on Aerofoils in Two-Dimensional Compressible Flow - A Theoretical Model," Royal Aircraft Establishment Technical Report 82128, 1983.
- 23) Brunet, L., "Conception et Discussion d'un Modele de Formation du Givre sur des Obstacles Varies," ONERA Note Technique 1986-6, Dec. 1986.
- 24) Berkowitz, B.M. and Riley, J.T., "Analytical Ice Shape Predictions for Flight in Natural Icing Conditions," NASA CR 182234 and DOT/FAA/CT-88/19, Dec. 1988.
- 25) Hansman, J.M., Yamaguchi, K., and Kazmierczak, M., "Revision to the Icing Model in LEWICE," AIAA Paper 91-0123, Jan. 1991.
- 26) Potapczuk, M.G. and Bidwell, C.S., "Numerical Simulation of Ice Growth on a MS-317 Swept Wing Geometry," AIAA Paper 91-0263, Jan. 1991.
- 27) Guffond, D.P., "Icing and De-Icing Test on a 1/4 Scale Rotor in the ONERA S1MA Wind Tunnel," AIAA Paper 86-0480, Jan. 1986.
- 28) Cebeci, T., "Effects of Environmentally Imposed Roughness on Airfoil Performance," NASA CR-179639, June 1987.
- 29) Shin, J., Berkowitz, B., Chen, H., and Cebeci, T., "Prediction of Ice Shapes and Their Effect on Airfoil Performance," AIAA Paper 91-0264, Jan. 1991.
- 30) Gray, V.H., "Prediction of Aerodynamic Penalties Caused by Ice Formation on Various Airfoils," NASA TN D-2166, 1964.
- 31) Bragg, M.B., "Rime Ice Accretion and Its Effect on Airfoil Performance," Ph.D. Dissertation, The Ohio State University, Columbus, OH, 1981.
- 32) Flemming, R.J., and Lednicer, D.A., "High Speed Ice Accretion on Rotorcraft Airfoils," NASA CR 3910, August 1985.
- 33) Bragg, M.B. and Spring, S.A., "An Experimental Study of the Flow Field about an Airfoil with Glaze Ice," AIAA Paper 87-0100, Jan. 1987.
- 34) Potapczuk, M.G., "Navier-Stokes Analysis of Airfoils with Leading Edge Ice Accretions," Ph.D. Dissertation, The University of Akron, Akron, OH, May 1989.
- 35) Bragg, M.B. and Khodadoust, A., "Experimental Measurements in a Large Separation Bubble due to a simulated Glaze Ice Accretion," AIAA Paper 88-0116, Jan. 1988.

- 36) Bragg, M.B. and Khodadoust, A., "Effect of Simulated Glaze Ice on a Rectangular Wing," AIAA Paper 89-0750, Jan. 1989.
- 37) Zaman, K.B.M.Q. and Potapczuk, M.G., "The Low Frequency Oscillation in the Flow over a NACA0012 Airfoil with an Iced Leading Edge," NASA TM-102018, June 1989.
- 38) Kwon, O.J. and Sankar, L.N., "Numerical Study of the Effects of Icing on Finite Wing Aerodynamics," AIAA Paper 90-0757, Jan. 1990.
- 39) Khodadoust, A. and Bragg, M.B., "Measured Aerodynamic Performance of a Swept Wing with a Simulated Ice Accretion," AIAA Paper 90-0490, Jan. 1990.
- 40) Al-Khalil, K.M., Keith, T.G., DeWitt, K.J., Nathman, J.K., and Dietrich, D.A., "Thermal Analysis of Engine Inlet Anti-icing Systems," AIAA Paper 88-0759, Jan. 1989.
- 41) Keith, T.G., DeWitt, K.J., Wright, W.B., and Masiulaniec, K.C., "Overview of Numerical Codes Developed for Predicting Electrothermal De-Icing of Aircraft Blades," AIAA Paper 88-0288, Jan. 1988.
- 42) Wright, W.B., Keith, T.G., and DeWitt K.J., "Numerical Simulation of Icing, Deicing, and Shedding," AIAA Paper 91-0665, Jan. 1991.
- 43) Chu, M., Scavuzzo, R.J., and Olsen, W.A., "Measurement of Adhesive Shear Strength of Impact Ice in an Icing Wind Tunnel," Proceedings of the 3rd International Workshop on the Atmospheric Icing of Structures, May 1986.
- 44) Scavuzzo, R.J., Chu, M., and Lam, P.D., "Development of a Composite Technique in the Determination of the Tensile Strength of Impact Ices," Proceedings of the 3rd International Workshop on the Atmospheric Icing of Structures, May 1986.
- 45) Scavuzzo, R.J., Chu, M.L., and Olsen, W.A., "Structural Properties of Impact Ices Accreted at Aircraft Surfaces," NASA CR-179580, Jan. 1987.
- 46) Martin, C. and Putt, J., "An Advanced Pneumatic Impulse Ice Protection System (PIIP) for Aircraft," AIAA-90-0492, January 1990.
- 47) Ramamurthy, S., Keith, T.G., DeWitt, K.J., Putt, J.C., Martin, C.A., and Leffel, K.L., "Numerical Modeling of an Advanced Pneumatic Impulse Ice Protection System (PIIP) for Aircraft," AIAA 91-0555, Jan. 1991.
- 48) Ide, R.F., "Liquid Water Content and Droplet Size Calibration of the NASA Lewis Icing Research Tunnel," NASA TM 102447, AVSCOM TM 89-C-014, AIAA-90-0669, January 1990.
- 49) Oldenburg, J.R., and Ide, R.F., "Comparison of Drop Size Distributions from Two Droplet Sizing Systems," NASA TM 1102520, AVSCOM TM 90-C-001, March, 1990.
- 50) Marek, C.J., and Bartlett, C.S., "Stability Relationship for Water Droplet Crystallization With the NASA Lewis Icing Spray," NASA TM 100220, AIAA-88-0289, January 1988.
- 51) Keller, R.G., "Measurement and Control of Simulated Environmental Icing Conditions in an Outdoor, Free Jet, Engine Ground Test Facility," Paper No. 7 in AGARD-CP-236, April, 1978.
- 52) Hunt, J.D., "Engine Icing Measurement Capabilities at the AEDC," Paper No. 6 in AGARD-CP-236, April, 1978.
- 53) Swift, R.D., "Icing Test Facilities at the National Gas Turbine Establishment," Paper No. 4 in AGARD-CP-236, April, 1978.
- 54) Bongrand, J., "Installations D'essais de Givrage," Paper No. 5 in AGARD-CP-236, April, 1978.
- 55) Ruff, G.A., "Analysis and Verification of the Icing Scaling Equations, Vol. I," AEDC-TR-85-30 (AD-A167976), Nov. 1985.
- 56) Bartlett, C.S., "An Analytical Study of Icing Similitude for Aircraft Engine Testing," AEDC-TR-86-26 (AD-A173713), DOT/FAA/CT-86-35, Oct. 1986.
- 57) Peterson, A.A., and Oldenburg, J.R., "Spray Nozzle Investigation for the Improved Helicopter Icing Spray System (IHSS)," AIAA-90-0666, January 1990.
- 58) Belte, D., and Woratschek, R., "Helicopter Icing Spray System (HISS) Evaluation and Improvements," USAAEFA Project No. 83-05-3, United States Army Aviation Engineering Flight Activity, Edwards Air Force Base, Ca 93523-5000, April 1986.

- 59) Mikkelsen, K., Juhasz, N., Ranaudo, R., and McKnight, R., "In-Flight Measurements of Wing Ice Shapes and Wing Section Drag Increases Caused by Natural Icing Conditions," NASA TM-87307, April 1986.
- 60) Belte, D. and Ranaudo, R.J., "Initial Results from the Joint NASA-Lewis/U.S. Army Icing Flight Research Tests," American Helicopter Society 45th Annual Forum Proceedings, May 1989.
- 61) Olsen, W.A., "Survey of Aircraft Icing Simulation Test Facilities in North America," NASA TM-81707, Feb. 1981.
- 62) Anon., "Rotorcraft Icing--Status and Prospects," AGARD Advisory Report No. 166, August 1981.
- 63) Anon., "Rotorcraft Icing--Progress and Potential," AGARD Advisory Report No. 223, September 1986.
- 64) Idzorek, J.J., "Observations on the Development of A Natural Refrigeration Icing Wind Tunnel," AIAA-87-0175, January 1987.
- 65) Tenison, G.V., "Development of a New Subsonic Icing Wind Tunnel," AIAA Paper No. 89-0773, January, 1989.
- 66) Van Fossen, G.J., Semonian, R.J., Olsen, W.A., and Shaw, R.J., "Heat Transfer Distributions around Nominal Ice Accretion Shapes Formed on a Cylinder in the NASA Lewis Icing Research Tunnel," AIAA Paper 84-0017, Jan. 1984.
- 67) Personne, P., "Effect de la Rugosite sur la Croissance du Givre a Faible Vitesse: Resultats Experimentaux et Modelisation," D.Sc. Thesis, L'Universite Blaise Pascal (Clermont-Ferrand II), June 1988.
- 68) Reehorst, A.L., and Richter, P.G., "New Methods and Materials for Molding and Casting Ice Formations," NASA TM 100126, Sep 1987.
- 69) Ingelman-Sundberg, M. and Trunov, O.K., "Wind Tunnel Investigation of the Hazardous Tail Stall due to Icing," Swedish-Soviet Working Group on Flight Safety, Joint Report No. JR-2, 1979.
- 70) Olsen, W., Shaw, R., and Newton, J., "Ice Shapes and the Resulting Drag Increase for a NACA 0012 Airfoil", NASA TM 83556, January 1984.
- 71) Flemming, R.J., Bond, T.H., and Britton, R.K., "Results of a Sub-Scale Model Rotor Icing Test," NASA TM 103709, AIAA-91-0660, January 1991.
- 72) Flemming, R.J., Bond, T.H., and Britton, R.K., "Model Rotor Icing Tests in the NASA Lewis Icing Research Tunnel," AGARD Specialists Meeting, Effects of Adverse Weather on Aerodynamics, Toulouse, France, 29 April-1 May 1991.
- 73) Bragg, M., Khodadoust, A., Soltani, R., Wells, S., and Kerho, M., "Effect of a Simulated Ice Accretion on the Aerodynamics of a Swept Wing," AIAA 91-0442, January 1991.
- 74) Goldberg, J. and Lardiere, B., "Developments in Expulsive Separation Ice Protection Blankets," AIAA Paper 89-0774, Jan. 1989.
- 75) Smith, S.O., and Zieve, P.B., "Thin Film Eddy Current Impulse Deicer", AIAA 90-0761, January 1990.
- 76) Zumwalt, G.W., Schrag, R.L., Bernhart, W.D., and Friedberg, R.A., "Electro-Impulse De-Icing Testing Analysis and Design," NASA CR-4175, 1988.
- 77) Bond, T.H., Shin, J., and Mesander G.A., "Advanced Ice Protection Systems Test in the NASA Lewis Icing Research Tunnel," NASA TM 103757, April 1991.
- 78) Al-Khalil, K., Keith, T., and Dewitt, K., "Further Development of an Anti-icing Runback Model," AIAA-91-0266, January 1991.
- 79) Ranaudo, R.J., Batterson, J.G., Reehorst, A.L., Bond, T.H., and O'mara, T.M., "Determination of Longitudinal Aerodynamic Derivatives Using Flight Data from an Icing Research Aircraft," AIAA Paper 89-0754, Jan. 1989.
- 80) Batterson, J.G., and O'Mara, T.M., "Estimation of Longitudinal Stability and Control Derivatives for an Icing Research Aircraft from Flight Data," NASA TM 4099, 1989.
- 81) Bilanin, A.J. "Problems in Understanding Aircraft Icing Dynamics," AIAA Paper 89-0735, Jan. 1989.

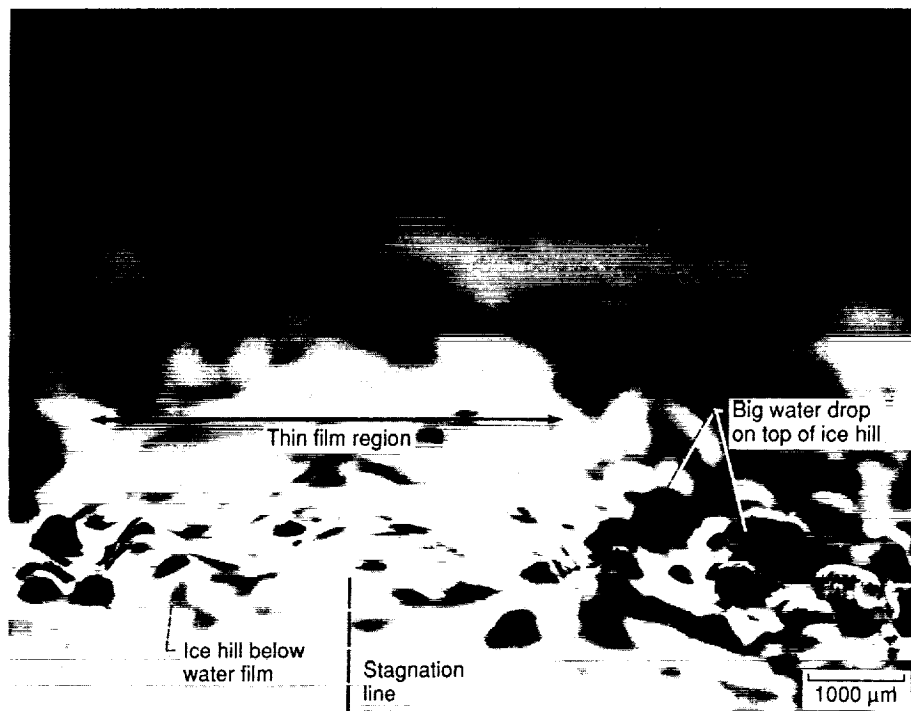


Figure 1.—Close-up grazing-angle still photos of ice formed at below freezing air temperature of -2°C .

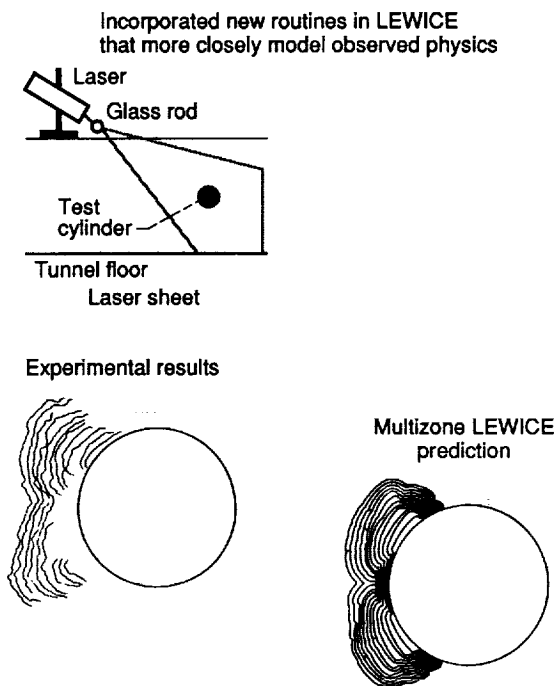


Figure 2.—Test set-up and results for ice layer growth on a cylinder.

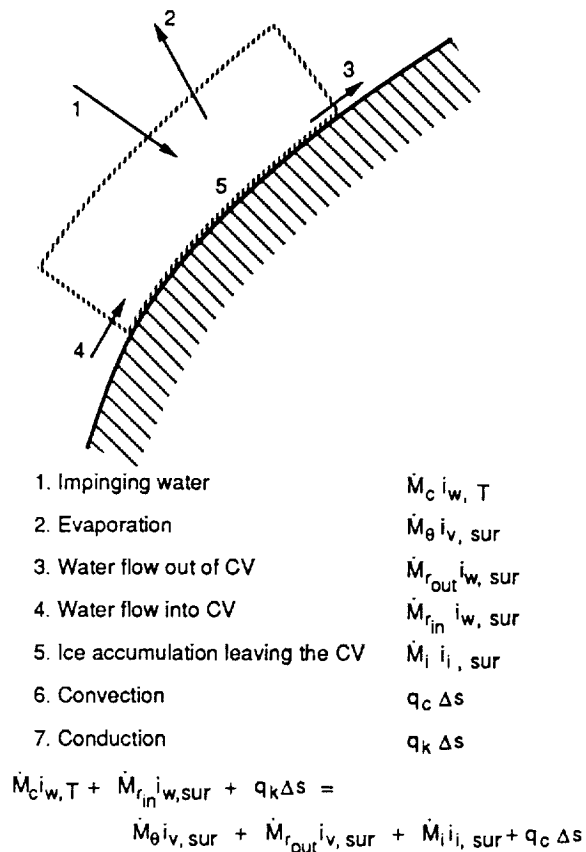


Figure 3.—Control volume for ice accretion energy balance.

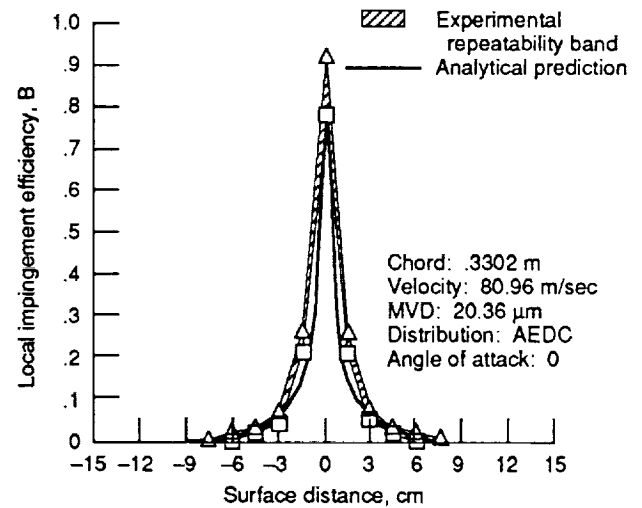


Figure 4.—Comparison of experimental repeatability and analytically predicted local impingement efficiency for a NACA 65-015 airfoil.

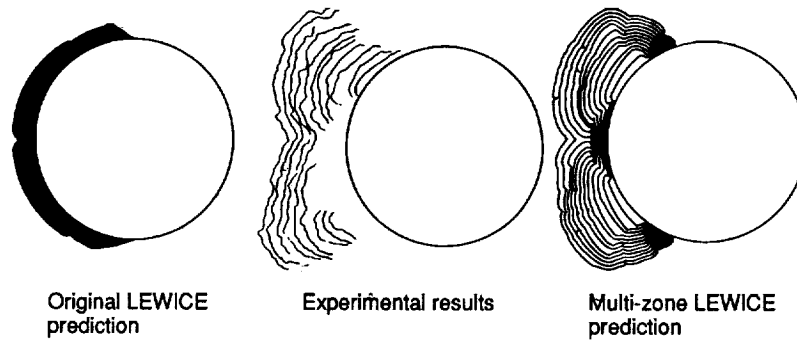


Figure 5.—Comparison of original LEWICE calculation to multi-zone LEWICE calculation for glaze ice accretion on a cylinder.

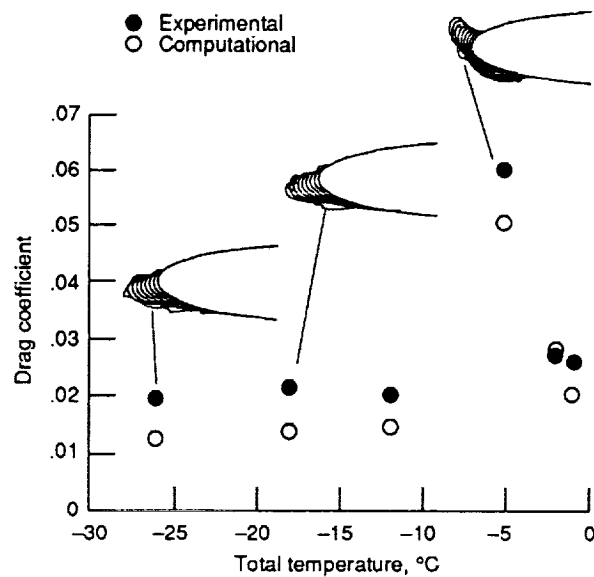


Figure 6.—LEWICE/IBL ice shape and drag coefficient predictions compared to experimental results.

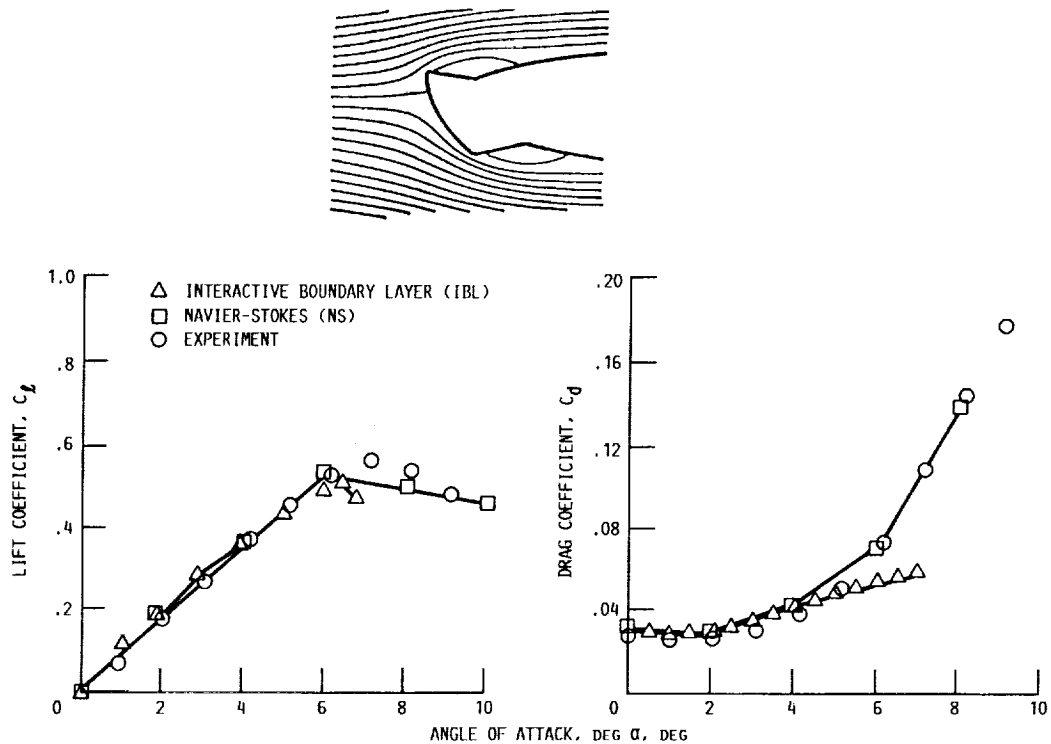


Figure 7.—Comparison of iced airfoil code predictions with experiment.

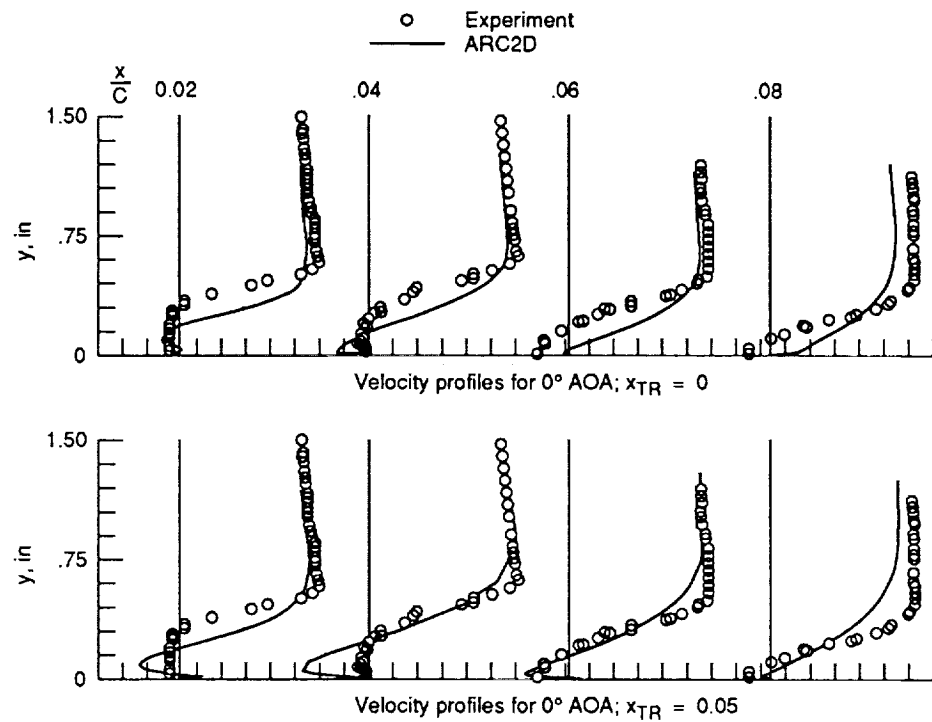


Figure 8.—Velocity profiles in the recirculation region aft of a glaze ice horn on a NACA 0012 airfoil.

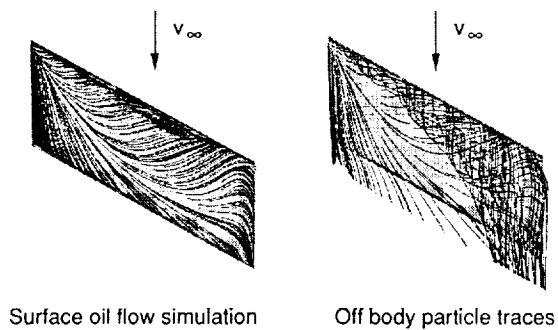


Figure 9.—Particle traces for flow over an iced swept semi-span wing at 8° angle of attack (NACA 0012 profile, 30° sweep angle).

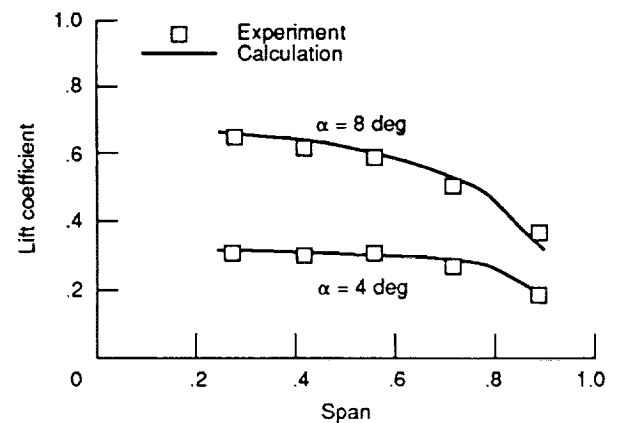


Figure 10.—Spanwise load distribution of an iced wing (NACA 0012 profile, 30° sweep angle) at 4° and 8° angle of attack.

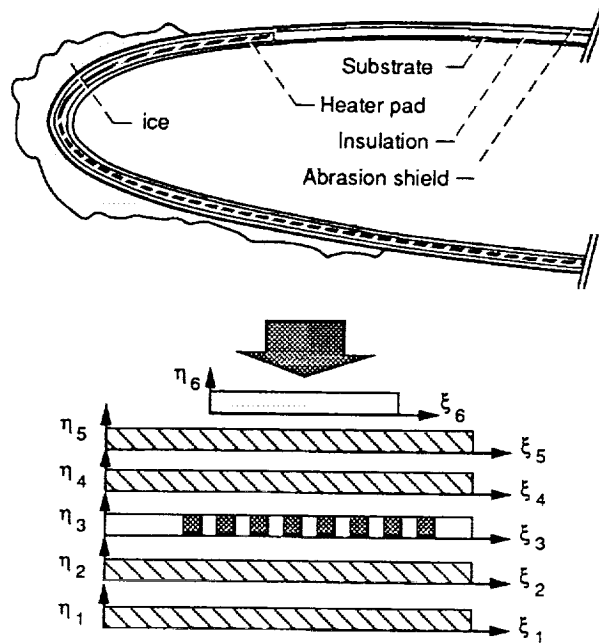


Figure 11.—Two-dimensional finite-difference model of an electrothermal heater. [Ref. 41].

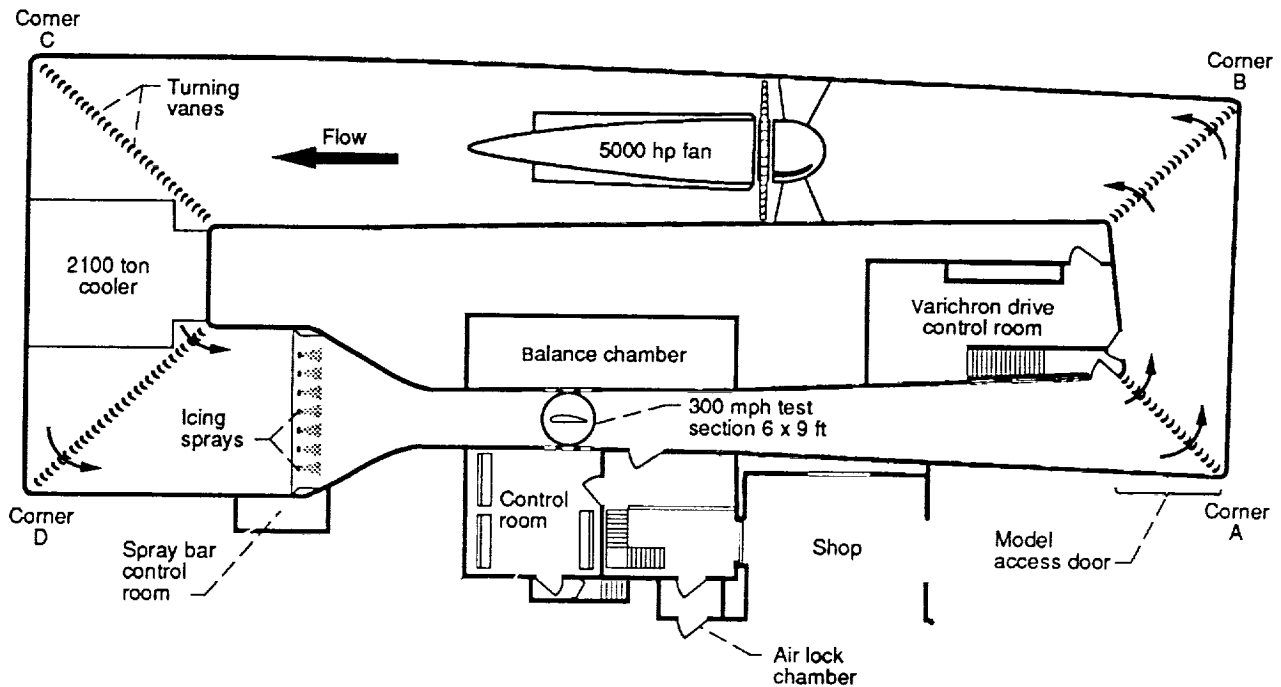


Figure 12.—Schematic of the NASA Lewis Research Center Icing Research Tunnel (IRT).

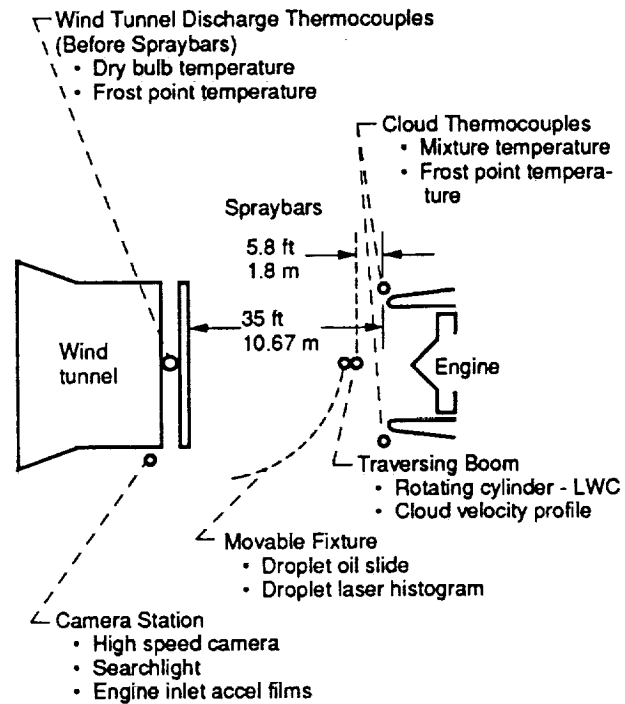


Figure 13.—Schematic of the General Electric engine icing test facility in Peebles, Ohio, USA. [Ref. 51].

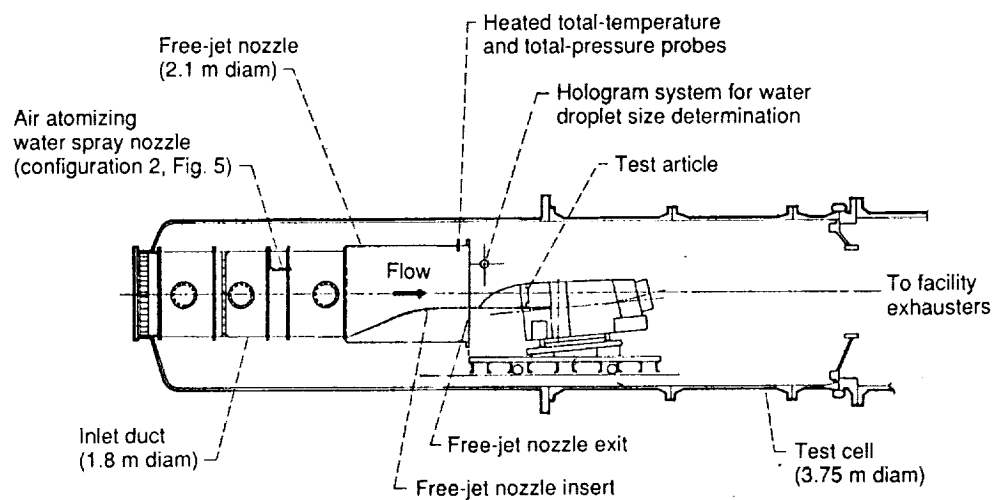


Figure 14.—Schematic of the AEDC engine icing test cell at Tullahoma, Tennessee, USA. [Ref. 52]

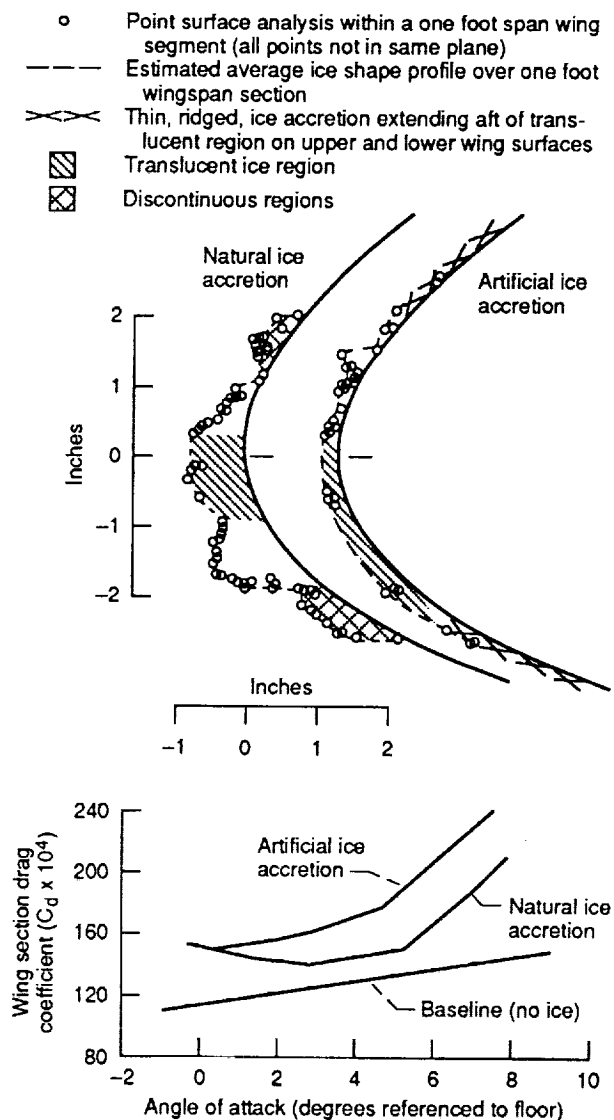


Figure 15.—Stereographic analysis of natural and artificial (HISS) ice accretions on NASA DH-6 wing section and resulting measured drag coefficients. [Ref. 60]

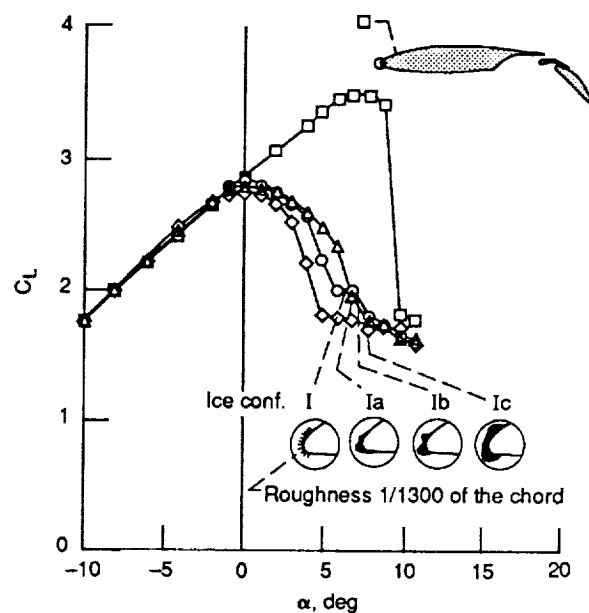


Figure 16.—The effect on $C_L(\alpha)$ and $C_{L_{max}}$ of ice shapes from the icing wind tunnel at the Research Institute of the Ministry of Civil Aviation, USSR. (Cruise condition with flaps extended). [Ref. 15]

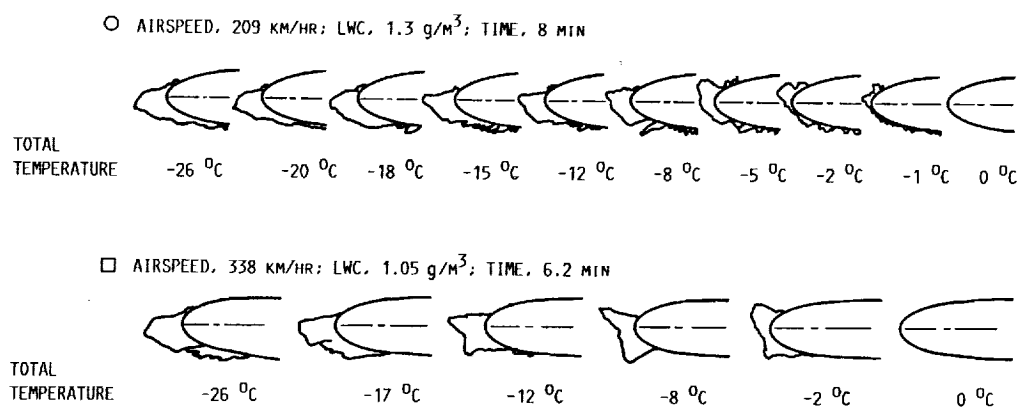


Figure 17.—The effect of total temperature on ice shape development. ($\text{LWC} \times V \times \text{time}$) = const. NACA 0012 airfoil at 4° angle of attack.

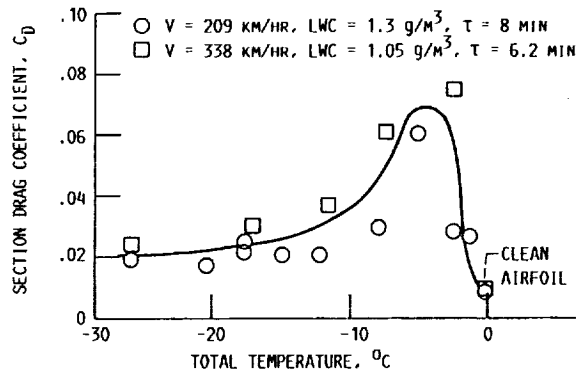


Figure 18.—The effect of total temperature on drag. (LWC x V x time) = const. NACA 0012 airfoil at 4° angle of attack.

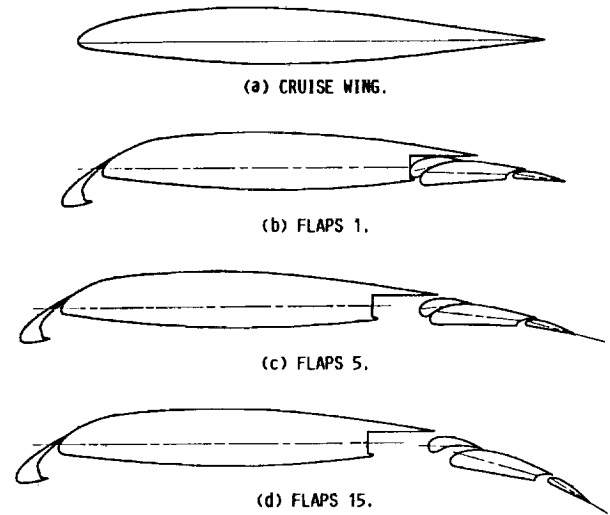


Figure 19.—Boeing 737-200 ADV wing section models tested in the NASA IRT.

Run number	Duration, min	Temperature, °F	Velocity, ft/s	LWC, g/m ³	MVD, μm
17	10	26	159	0.92	14.4

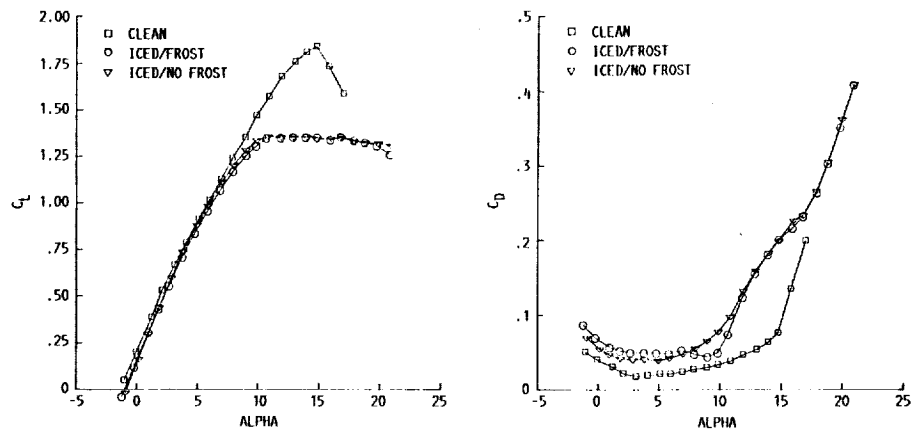


Figure 20.—Changes in lift and drag resulting from glaze ice growth on the Boeing 737-200 ADV wing model in the flaps 1 configuration.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



Figure 21.—Swept, finite wing with simulated ice on the leading edge installed in the University of Illinois subsonic wind tunnel.

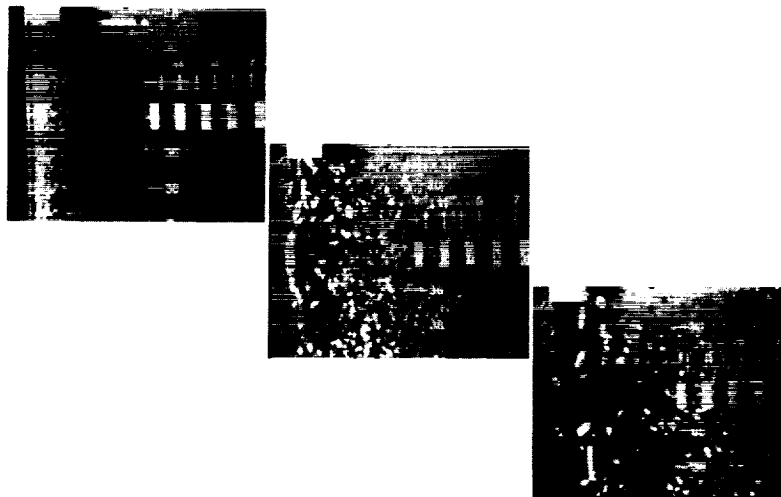


Figure 22.—High speed video of ice shedding event during activation of a low power de-icing system.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

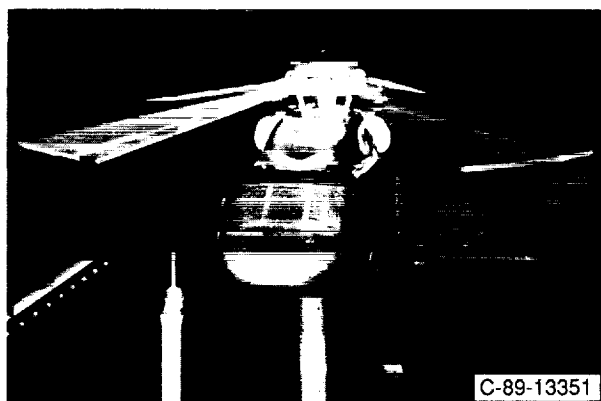


Figure 23.—Powered force model operating during simulated icing encounter in NASA Lewis Icing Research Tunnel.

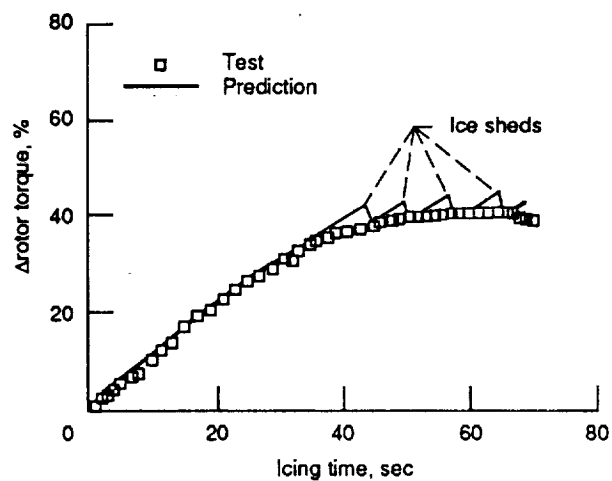


Figure 24.—Comparison of calculated and measured torque rise of PFM rotor during simulated icing encounter in the NASA IRT.

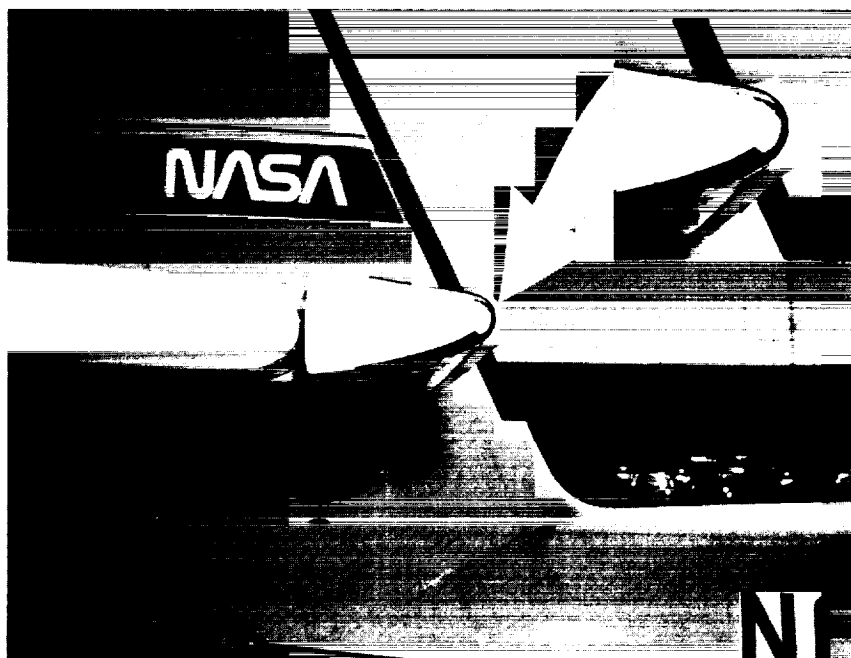


Figure 25.—Simulated ice shape attached to tail of NASA DHC-6 for evaluation of changes to stability and control characteristics.

Report Documentation Page

1. Report No. NASA TM -104366		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Icing Simulation: A Survey of Computer Models and Experimental Facilities				5. Report Date	
				6. Performing Organization Code	
7. Author(s) M.G. Potapczuk and J.J. Reinmann				8. Performing Organization Report No. E -6164	
				10. Work Unit No. 505-68-10	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135 - 3191				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546 - 0001				14. Sponsoring Agency Code	
15. Supplementary Notes Prepared for the 68th AGARD Fluid Dynamics Panel Specialists Meeting, Toulouse, France, April 29—May 1, 1991. Responsible person, M.G. Potapczuk, (216) 433-3919.					
16. Abstract This paper is a survey of the current methods for simulation of the response of an aircraft subsystem to an icing encounter. The topics discussed include: 1) computer code modeling of aircraft icing and performance degradation, 2) evaluation of experimental facility simulation capabilities, and 3) ice protection system evaluation tests in simulated icing conditions. Current research, which is focussed on upgrading simulation fidelity of both experimental and computational methods, is discussed. The need for increased understanding of the physical processes governing ice accretion, ice shedding, and iced airfoil aerodynamics is examined.					
17. Key Words (Suggested by Author(s)) Icing Aircraft hazards Aeronautics				18. Distribution Statement Unclassified - Unlimited Subject Category 02	
19. Security Classif. (of the report) Unclassified		20. Security Classif. (of this page) Unclassified		22. Price* A03	
				21. No. of pages 28	